

## Program and Abstract Volume

# Venus Geochemistry:

Progress, Prospects, and New Missions

February 26–27, 2009 • Houston, Texas

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Abstracts in this volume may be cited as

Author A. B. (2009) Title of abstract. In *Workshop on Venus Geochemistry: Progress, Prospects, and New Missions*, p. XX. LPI Contribution No. 1470, Lunar and Planetary Institute, Houston.

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ISSN No. 0161-5297

## Preface

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This volume contains abstracts that have been accepted for presentation at the Workshop on Venus Geochemistry: Progress, Prospects, and New Missions, February 26–27, 2009, Houston, Texas.

Administration and publications support for this meeting were provided by the staff of the Publications and Program Services Department at the Lunar and Planetary Institute.



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# Program

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**Thursday, February 26, 2009**  
**GEOLOGICAL AND GEOPHYSICAL CONSTRAINTS**  
**8:30 a.m. Lone Star Room**

- 8:30 a.m. Treiman A. H. \* Ocampo A.  
*Welcome and Meeting Logistics*
- 8:45 a.m. Kiefer W. S. \* [INVITED]  
*The Geology and Geophysics of Venus*
- 9:15 a.m. Head J. W. \* Ivanov M. A. Basilevsky A. T.  
*Geological Evidence for Petrogenetic Diversity on Venus: Implications for Future Exploration Strategies [#2025]*
- 9:30 a.m. Gilmore M. S. \*  
*Tessera Terrain is a Fundamental Geochemical Target [#2022]*
- 9:45 a.m. Hansen V. L. \*  
*Is There a Genetic Association Between Ribbon Tessera Terrain and Shield Terrain, Venus? [#2012]*
- 10:00 a.m. Ivanov M. A. \* Head J. W.  
*An Analysis of the Nature of Tessera Materials on Venus [#2002]*
- 10:15 a.m. BREAK
- 10:30 a.m. Marov M. Ya. \* [INVITED]  
*VENERA and VEGA Missions to Venus: Historical Highlights [#2026]*
- 11:00 a.m. Kargel J. S. \* [INVITED]  
*Volcanology of the Venera and VEGA Landing Sites*
- 11:30 a.m. McGovern P. J. \* Filiberto J.  
*Interactions of Mechanical Controls on Magma Emplacement with the Petrology of Volcanic Edifice-building Flows on Venus [#2023]*
- 11:45 a.m. Elkins-Tanton L. T. \* Smrekar S. E.  
*Magmatism on Venus: Upside-Down Melting in Gravitational Instabilities and a Possible Analog in the Siberian Large Igneous Province [#2009]*
- 12:00 p.m. LUNCH



**Thursday, February 26, 2009**  
**CHEMICAL ANALYSES AND PLANETARY INFERENCES**  
**1:30 p.m. Lone Star Room**

- 1:30 p.m. Treiman A. H. \* [INVITED]  
*Venus Geochemistry and Bulk Composition*
- 1:45 p.m. Treiman A. H. \*  
*Venus' Bulk and Mantle Compositions: Are Venus and Earth Really Twins? [#2016]*
- 2:00 p.m. Kargel J. S. \*  
*Soviet Lander and Magellan Data Point Toward Earthlike Venus Geochemistry and Volcanology, With Some Differences, and Many Questions [#2014]*
- 2:15 p.m. Filiberto J. \*  
*Magmatic Diversity on Venus: Constraints from Terrestrial Analog Experiments [#2017]*
- 2:30 p.m. Jones J. H. \*  
*Core Formation on the Terrestrial Planets: Comparative Planetology of the Earth, Moon, Mars, Vesta, and Venus [#2018]*
- 2:45 p.m. Basilevsky A. T. \* Head J. W.  
*Geochemical Aspects of the Geological History of Venus [#2001]*
- 3:00 p.m. BREAK
- 3:30 p.m. Kiefer W. S. \* Filiberto J.  
*Melting Venus: Potential Geochemical Diagnostics of Mantle Source Depth [#2005]*
- 3:45 p.m. Kreslavsky M. A. \*  
*Surficial Deposits and Access to Materials with Known Geological Context on Venus [#2019]*
- 4:00 p.m. DISCUSSION AND SHORT CONTRIBUTIONS

**Thursday, February 26, 2009**  
**POSTER SESSION**  
**Lone Star Room**

Clegg S. M. Barefield J. E. Wiens R. C. Quick C. R. Sharma S. K. Misra A. K. Dyar M. D.

McCanta M. C. Elkins-Tanton L.

*Venus Geochemical Analysis by Remote Raman — Laser Induced Breakdown Spectroscopy (Raman-LIBS) [#2013]*

Migliorini A. Grassi D. Piccioni G. Drossart P. Cardesin-Moinelo A. VIRTIS-VEX Team

*Thermal Structure in the Venusian Atmosphere: Diurnal and Annual Variations [#2008]*

Michael P. J.

*Sulfur Behavior in Terrestrial Basaltic Magmas: Insights for the Behavior of Volcanic Sulfur on Venus [#2020]*

**Friday, February 27, 2009**  
**ATMOSPHERE AND SURFACE-ATMOSPHERE INTERACTION**  
**8:30 a.m. Lone Star Room**

- 8:30 a.m. Bullock M. A. \* [INVITED]  
*Venus Atmosphere*
- 8:45 a.m. Yung Y. L. \* Liang M. C.  
*Atmospheric Constraints on Sulfur Reaction Fluxes at the Surface of Venus* [#2028]
- 9:15 a.m. Mahieux A. \* Wilquet V. Drummond R. Vandaele A. C. Federova A.  
Belyaev D. Korabiev O. Bertaux J. L.  
*Trace Gas Constituents of the Venus Mesosphere Measured by SPICAV/SOIR Onboard Venus Express* [#2007]
- 9:30 a.m. Visscher S. \* [INVITED]  
*Surface-Atmosphere Interactions*
- 10:00 a.m. Treiman A. H. Schwenzer S. P. \*  
*Basalt-Atmosphere Interaction on Venus: Preliminary Results on Weathering of Minerals and Bulk Rock* [#2011]
- 10:15 a.m. BREAK

**Friday, February 27, 2009**  
**CURRENT MISSION AND FUTURE INSTRUMENTS**  
**10:45 a.m. Lone Star Room**

- 10:45 a.m. Mueller N. \* Helbert J. Hashimoto G. L. Tsang C. C. C. Erard S. Piccioni G.  
Drossart P. VIRTIS-VEX Team  
*Venus Surface Thermal Emission Observed by VIRTIS on Venus Express* [#2004]
- 11:00 a.m. Helbert J. \* Maturilli A. Müller N.  
*Facing the Heat — Obtaining Near Infrared Real Emissivity Spectra at Venus Surface Temperatures* [#2010]
- 11:15 a.m. Grimm R. E. \* Delory G. T.  
*Magnetotelluric Sounding of the Interior of Venus* [#2015]
- 11:30 a.m. Wang A. \*  
*Planetary Raman Spectroscopic Study for Understanding Venus Evolution History* [#2003]
- 11:45 a.m. LUNCH

**Friday, February 27, 2009**  
**VENUS AS A TERRESTRIAL PLANET — AND WHAT TO DO ABOUT IT**  
**1:30 p.m. Lone Star Room**

- 1:30 p.m. Grinspoon D. H. \* Bullock M. A. Head J. W. [INVITED]  
*The History of Venus* [#2027]
- 2:00 p.m. Bullock M. A. \* Grinspoon D. H.  
*The Role of Sulfur in Detecting Recent Climate Change on Venus* [#2024]
- 2:15 p.m. Zolotov M. Yu. \* Mironenko M. V.  
*On the Composition of Putative Oceans on Early Venus* [#2021]
- 2:30 p.m. DISCUSSION FOR WORKSHOP REPORT INTO DECADEAL SURVEY
- 3:30 p.m. MEETING ADJOURN

## IN-SITU AERIAL EXPLORATION OF VENUS BY BALLOON - SCIENCE OBJECTIVES AND MISSION ARCHITECTURE. K.H. Baines<sup>1</sup>, S. K. Atreya<sup>2</sup>, D. Crisp<sup>3</sup>, J. L. Hall<sup>4</sup>, V. V. Kerzhanovich<sup>5</sup>, S. S. Limaye<sup>6</sup>,

K. Zahnle<sup>7</sup>, <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology (MS 183-601, 4800 Oak Grove Dr., Pasadena, CA 91109; kevin.baines@jpl.nasa.gov), <sup>2</sup> University of Michigan, Dept of Atmospheric, Oceanic, and Space Sciences (2455 Hayward St., Ann Arbor, MI 48109), <sup>3</sup>Jet Propulsion Laboratory, California Institute of Technology (MS 183-501, 4800 Oak Grove Dr., Pasadena, CA 91109), <sup>4</sup>Jet Propulsion Laboratory, California Institute of Technology (MS 82-105, 4800 Oak Grove Dr., Pasadena, CA 91109), <sup>5</sup>Jet Propulsion Laboratory, California Institute of Technology (MS 198-219, 4800 Oak Grove Dr., Pasadena, CA 91109), <sup>6</sup>University of Wisconsin-Madison, Space Science and Engineering Center (1226 West Dayton St., Madison, WI 53706), <sup>7</sup>NASA/Ames Research Center (M/S 245-3, Moffett Field, CA 94035).

**Introduction:** Following the trailblazing flights of the 1985 twin Soviet VEGA balloons, missions to fly in the skies of Venus have been proposed to both NASA's Discovery and ESA's Cosmic Visions programs, and are a key element of the recently-completed Venus Flagship Mission study. Such missions will answer fundamental science issues highlighted in a variety of high-level NASA-authorized science documents in recent years, including the Decadal Study, various NASA roadmaps, and recommendations coming out of the Venus Exploration Analysis Group (VEXAG). Such missions would in particular address key questions of Venus's origin, evolution, and current state, including detailed measurements of (1) trace gases associated with Venus's active photo- and thermo-chemistry and (2) measurements of vertical motions and local temperature which characterize convective and wave processes. As an example of what can be done with small class missions (less than \$500 M), the Venus Aerostatic-Lift Observatory for in-situ Research (VALOR) Discovery mission concept will be discussed. Floating in Venus's rapid windstream near an altitude of 55 km, VALOR's balloon-borne science observatory will sample rare gases and trace chemicals and measure vertical and horizontal motions and cloud aerosols within Venus's dynamic middle cloud layer. The balloon will explore a variety of distinctive dynamical/meteorological regimes within Venus's energetic atmosphere as it drifts northward over several weeks from the convective temperate region through the wave-populated mid-latitudes and then poleward to the exceedingly cloudy north polar cyclonic vortex. The mission will test a variety of scenarios for the origin, formation, and evolution of Venus by sampling all the noble gases and their isotopes, especially the heaviest elements never reliably measured previously, xenon and krypton. Riding the gravity and planetary waves of Venus à la the VEGA balloons in 1985, the VALOR balloon would sample in particular the chemistry and dynamics of Venus's sulfur-cloud meteorology.

Tracked by an array of Earth-based telescopes, all three components of winds - zonal, meridional, and vertical - would be measured with unprecedented precision over nearly all longitudes and over 40 degrees of latitude. Such measurements will help in developing our fundamental understanding of (1) the circulation of Venus, including the roles of waves and meridional motions in powering the planet's poorly-understood super-rotation, (2) the nature of Venus's sulfur cycle, key to Venus's current climate, and (3) how Earth's neighbor formed and evolved over the aeons.

**GEOCHEMICAL ASPECTS OF THE GEOLOGICAL HISTORY OF VENUS.** A.T. Basilevsky<sup>1,2</sup> and J.W. Head<sup>2</sup>, <sup>1</sup>Vernadsky Institute of Geochemistry and Analytical Chemistry, RAS, Moscow 119991 Russia, [atbas@geokhi.ru](mailto:atbas@geokhi.ru); <sup>2</sup>Dept. Geological Sci., Brown University, Providence, RI, 02912 USA, [James\\_Head@Brown.edu](mailto:James_Head@Brown.edu)

**Introduction:** The current knowledge of the geological history of Venus can be interpreted in terms of the history of the geochemical environments on this planet. One can distinguish two parts of the geologic history of Venus: the later part, for which we have morphological records supplemented by geochemical measurements on the surface and in the atmosphere, and the earlier part, for which there is indirect evidence recorded in some compositional characteristics of the atmosphere of the planet.

**The latter part of the history:** For the later part, which occupies the last 0.5-1 b.y. of the history of Venus [1], one can consider the geochemistry of the processes occurring in the crust and in the upper mantle, and the surface geochemistry.

*Geochemical processes in the crust and upper mantle* are obviously the magmatic processes. Considering the known dryness and other parameters of the atmosphere, it is logical to suggest that hydrothermal activity is not appropriate in the crust and probably on Venus magmas are dryer than terrestrial magmas. Some clue to the composition of Venus magmas can be found from the characteristics of the observed volcanic formations.

The most widespread (> 80 % of the surface) volcanic formations are represented by plains [e.g., 2-4]. Most of these show either extensive and morphologically very distinct flow-like features, obviously formed by solidified lava flows, or clusters of kms-size gently-sloping shields. Numerous larger volcanic constructs, many of which are more than a hundred kilometers in diameter, are also seen [5]; however the area they occupy is relatively small. These constructs are typically gently-sloped. The gentle slopes of the majority of the Venus volcanic constructs and the large areal sizes of lava flows on the generally horizontal plains, suggest low lava viscosity.

Considering that the most widespread volcanic plains on the Earth and the Moon are assemblages of basaltic lavas which, in turn, are expected products of partial melting of the chondrite-like materials composing the silicate parts of all terrestrial planets [6], one can suggest that the majority of the observed products of Venus volcanism are also basaltic. This is in agreement with the deduced low viscosity of the lavas and is supported by geochemical measurements [7] in seven sites where the Venera-Vega probes landed (all on the plains). So the dominant geochemical processes in the Venus crust and the upper mantle are probably partial

melting of the interior, producing basaltic melts and the subsequent crystallization of these melts. The latter, when it occurs in the erupted lavas, simply quenches the melt without significant geochemical effects, but when crystallization occurs in the plutonic environment, compositional differentiation may occur. The diversity of chemistry, especially of the potassium contents [7], observed for the Venera-Vega sites suggests that compositional differentiation indeed took place, either during magma-forming partial melting, or in the crystallization within magmatic plutons, or both.

There are two morphologic units on Venus whose characteristics may suggest non-basaltic composition. One is represented by the so-called steep-sided domes of obvious volcanic origin, typically a few tens of kilometers in diameter [8]. The steepness of the dome slopes is usually considered as an indication of high lava viscosity, which in turn may suggest non-basaltic, more silicic composition [e.g., 9]. But high viscosity might also be due to the abundance of gas bubbles in the lavas [9] or to an increased content of dissolved water and differences in lava crystallinity [10]. It was also suggested by [11] that the domes may simply be the low-eruption rate basaltic volcanoes. So, the non-basaltic composition of the steep sided domes on Venus is possible, but not certain. If however these domes are composed of non-basaltic lavas, the latter could appear as a result of partial melting within the essentially basaltic crust.

Another unit of potential non-basaltic composition is tessera terrain, which forms blocks of different sizes, up to thousands kilometers across occupying altogether ~10% of the planet surface [12]. Massifs of this highly tectonized unit typically stand above the surrounding basaltic plains. This may suggest that they are composed of the materials less dense than basalts. As an option however this higher hypsometric position could be due to a greater thickness of basaltic crust.

Nikolaeva et al. [13] compiled several lines of indications that tessera might be composed of geochemically more differentiated materials than basalts, for example, essentially feldspatic materials such as terrestrial silicic to intermediate rocks and lunar anorthosites. Later, joint analysis of the gravity field and topography of Ishtar Terra led to the conclusion that some parts of the Maxwell Montes highland, consisting of material structurally similar to tessera, could be composed of material less dense than basalt and be silicic [14].

Meanwhile, Ivanov [15] observed evidence that tessera was formed at the expense of some precursor plains. Suggesting that these plains have a basaltic composition, he concluded that the tessera material could be basaltic (see also Ivanov and Head, this volume). No Venera-Vega geochemical probe landed on tessera terrain; thus, all information about its composition is still indirect.

*Surface geochemistry* on Venus in the latter part of its history is controlled by the chemical interaction of the surface materials with the atmosphere. The latter is dominated by CO<sub>2</sub> and has minor admixtures of other gases. Physical-chemical calculations [see e.g., 16-17] suggest several effects of surface-atmosphere interactions on Venus, including: 1) oxidation and sulfurization of surface rocks through gas-solid-type reactions; 2) isochemical weathering of individual solid phases with respect to elements being nonvolatile at surface temperatures on Venus (e.g., Al, Si, Mg, Fe, Ca, Na); and 3) a strong elevational effect for the chemistry and physics of gas-surface interactions. Current hydration of anhydrous phases is considered to be unlikely and any original hydrated phases (if they existed at all) would be dehydrated [17]. These calculations, however, suffer from the poor knowledge of the redox state of the lower part of the atmosphere on Venus.

An essential characteristic of the surface geochemistry of Venus is that the surface materials could acquire some chemical elements from the atmosphere (S, O), but most of their chemical components should stay practically immobile. So the chemical weathering effects on Venus are expected to be limited to a very thin surface layer. Based on the observed absence of impact craters smaller than 1 km in diameter on the hundreds of million of years old plains suggests that the currently observed large mass of the atmosphere of Venus (which is also a cause of the high surface temperature) was also characteristic of the past.

**The earlier part of the history of Venus.** The most striking and least doubtful piece of evidence on this is the discovery by one of the Pioneer Venus probes of the so-called deuterium anomaly, a D/H ratio larger by a factor of 150 than it is in Earth's oceans [18]. This implies significant hydrogen escape from the planet, suggesting that early in its history Venus could have lost a large amount of water. Some models even suggest the presence of oceans on Venus at that time [e.g., 19]. We may only guess about the geotectonic environment of Venus at that time. An abundance of water could affect not only the surface, but also influence the interior of Venus. This in turn could change the rheology of crustal materials [20] and even favor plate tectonics and its related geochemical aspects, including

formation of felsic materials [21]. So if tessera terrain is found to be felsic it could be a message of that time.

If water on the surface of Venus during that time was present in liquid form, this requires a relatively cool environment, this should result in Earth-like surface processes, including hydrous geochemistry with significant compositional differentiation. But if this abundant water was present as vapor in the hot dense atmosphere, the surface geochemical processes would perhaps be similar to pneumatolytic processes in the contact zones of terrestrial magmatic bodies. This could lead, for example, to transportation through the atmosphere of some rock components (e.g., SiO<sub>2</sub>) from the hotter lowlands to the colder highlands.

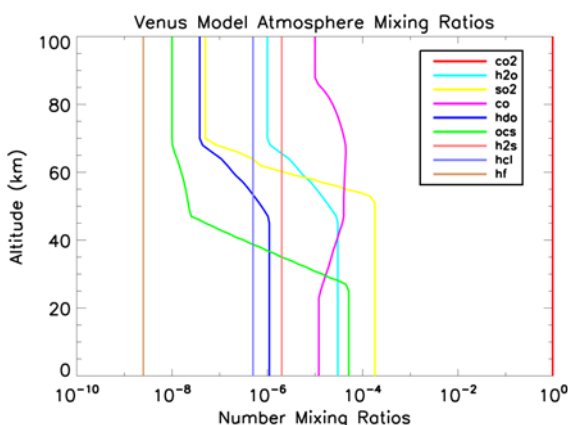
**Conclusions.** The current knowledge of the geochemistry of Venus is rather poor and essentially hypothetical. To make significant progress in this area new missions to Venus are necessary. They should provide much more reliable data on the minor chemical components of the atmosphere of Venus, especially on the components indicative of the redox state of the lower part of the atmosphere. New geochemical measurements of the surface composition are crucial. They should provide information on the compositions of the geologic units not directly geochemically investigated earlier, first of all, landing on tessera terrain and then on some other units [22]. These new missions should be equipped with instruments providing more information than acquired by the Venera-Vega landers. A sample return mission to Venus, although more difficult, should be on the near horizon.

**References:** [1] McKinnon W. et al. (1997) Venus II, Univ. of Arizona Press, 969-1014. [2] Head J. W. et al (1992) JGR, 97, 13,153-13. [3] Basilevsky A. T. & Head J. W. (2000) PSS, 48, 75-111. [4] Ivanov M. A. (2007) LPSC-39, abs. 1017. [5] Crumpler L. S. et al. (1997) Venus II, Univ. Ariz Press, 969-1014. [6] Basaltic Volcanism on the Terrestrial Planets (1981). Pergamon Press, Inc., New York. 1286 pp. [7] Surkov Y. A. (1997) Exploration of Terrestrial Planets from Spacecraft, John Wiley, 446 pp. [8] Ivanov and Head (1999) JGR, 104, 18907-18924. [9] Pavri B. et al (1992) JGR, 97, 13,479-13,493. [10] Bridges N. T. (1995) GRL, 22, 2781-2784. [11] Fink J. H. & Griffiths R. W. (1998) JGR, 103, 537-545. [12] Ivanov and Head (1996) JGR, 101, 14861-14908. [13] Nikolaeva O. V. et al. (1992) Venus Geology, Geochemistry and Geophysics, Univ. Ariz Press, 129-139. [14] Kuchinskas A. B. et al. (1996) JGR, 101, 4725-4736. [15] Ivanov M.A. (2001) SSR, 35, 1-17. [16] Fegley B. Jr. (2003) Treatise on Geochemistry, 1, 487-507. [17] Zolotov M. Yu. (2007) Treatise on Geochemistry, 10, 349-370. [18] Donahue T. M. et al (1982) Science, 216, 630-633., and A. J. Watson, Venus was wet: A measurement of the ratio of D to H, , 1982. [19] Grinspoon D. H. & Bullock M. A. (2003) BAAS, 35, 44-03. [20] Mackwell S. J. et al (1998) JGR, 103, 975-984. [21] Taylor R. S. & McLennan S. (2008) Planetary crusts. Cambridge Univ. Press, 400 pp. [22] Basilevsky A. T. et al. (2007) PSS, 55, 2097-2112.



**THE ROLE OF SULFUR IN DETECTING RECENT CLIMATE CHANGE ON VENUS.** M. A. Bullock<sup>1</sup> and D. H. Grinspoon<sup>2</sup>, <sup>1</sup>Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302 (bullock@boulder.swri.edu), <sup>2</sup>Denver Museum of Nature & Science, Denver, CO (david.grinspoon@dmns.org).

**Introduction:** Even with the extremely limited data on the deep atmosphere and surface of Venus, it is clear that chemical reactions are vigorous near the surface. The evidence for this are the steep gradients in sub-cloud mixing ratios that have been observed for CO, SO<sub>2</sub>, OCS and other trace species (Fig. 1). Moreover, due to the high temperatures and pressures at the surface, it is also likely that reactions between atmospheric gases and surface minerals are ongoing, influencing global chemical cycles and the composition of the near-surface crust.



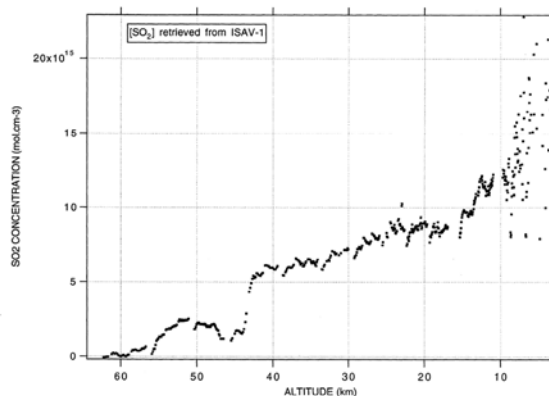
**Figure 1.** Atmospheric mixing ratios of the nine most abundant gases in the Venus atmosphere. Note the strong gradients in OCS, CO, and SO<sub>2</sub> beneath the clouds.

**Atmospheric SO<sub>2</sub>:** Of particular interest are the sulfur gases, since extrapolation of the Pioneer Venus GCMS results from 22 km indicate that SO<sub>2</sub> abundance near the surface is about 180 ppm. Furthermore, laboratory work has shown that the equilibrium abundance of this gas should be about 2 ppm, but that it reacts rapidly with carbonates under Venus like conditions. These experiments led Fegley and Prinn [1] to conclude that the residence time of SO<sub>2</sub> in the Venus atmosphere was about 2 My, and that volcanism at a rate of 0.4 to 11 km<sup>3</sup>/year is presently necessary to sustain the clouds. Using these laboratory data, reaction/diffusion calculations to model the transport of atmospheric gases to fresh reaction sites within the surface, and a simple microphysical cloud model, Bullock and Grinspoon further refined the estimate of SO<sub>2</sub> atmospheric residence time to be about 30 My [2]. An independent analysis of the present-day volcanic rate, from the observed incidence of crater embayment and

a Monte Carlo cratering and volcanic activity model, concluded that the recent volcanic rate on Venus has to be on the order of 0.4 km<sup>3</sup>/yr [3].

Given the above, it is reasonable to conclude that if volcanism ever ceased or severely declined on Venus for 50 My, SO<sub>2</sub> could have been drawn down into the surface and the clouds would have dissipated. Venus' appearance in Earth's night sky would have been dramatically affected, since its albedo would have decreased from 0.8 to 0.4. Surprisingly, however, climate models show that Venus would have not gotten hotter, since Rayleigh scattering by the thick atmosphere would have kept 40% of the incident light reflecting into space, and because the clouds themselves are a potent greenhouse agent [2].

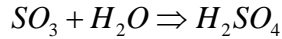
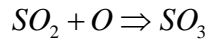
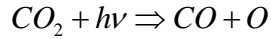
There are several problems and opportunities with this proposed SO<sub>2</sub> scenario. One of the most interesting comes from observations of SO<sub>2</sub> much lower in the atmosphere, near 12 km, from the Vega UV spectrometers. Bertaux and colleagues showed that SO<sub>2</sub> mixing ratio declines dramatically towards the surface (Fig. 2), and approaches something like the equilibrium value over carbonate [4]. Although this would indicate that reactions between atmospheric SO<sub>2</sub> and the surface are not occurring, it also means that an explanation for the atmospheric reactions that are responsible for such a wholesale destruction of SO<sub>2</sub> in the deep atmosphere is necessary. There were numerous problems with the UV spectrometers on the Vega descent probes however. New data from a deep atmosphere probe will be necessary to resolve this issue.



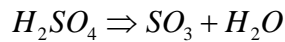
**Figure 2.** Vertical profile of SO<sub>2</sub> number density retrieved by the Vega 1 UV spectrometer. From [4].

**The Venus Sulfur Cycle:** Sulfur gases exist in the Venus atmosphere in significant quantities at the full

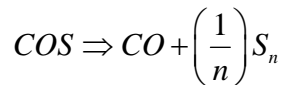
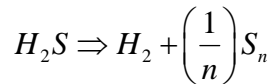
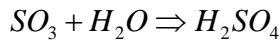
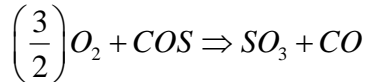
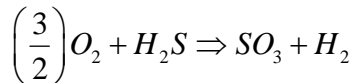
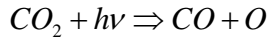
range of oxidation states, from  $H_2S$  to  $SO_3$ . The Venus sulfur cycle is often divided into three subcycles. The *fast atmospheric cycle* transfers sulfur between vapor and sulfuric acid liquid aerosol reservoirs. Above and within the clouds, it is driven by photochemistry and produces sulfuric acid cloud aerosols via the net reactions:



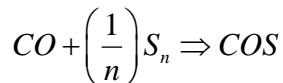
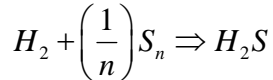
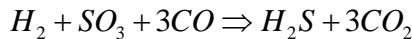
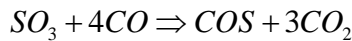
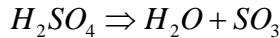
In the hot sub-cloud region sulfur to its largest reservoir,  $SO_2$ . The net reactions can be written:



The *slow atmospheric cycle* transfers sulfur between liquid acidic aerosols and sulfur gases of different oxidation states. Within the clouds,



Below the clouds, the return reactions are:



The third, or *geologic cycle*, produces atmospheric  $H_2S$  and  $COS$  from the oxidation of pyrite [6], and draws down  $SO_2$  from its reaction with carbonate, as discussed above.

Yung and Liang recently made the point that the transfer of sulfur between atmospheric reservoirs ( $SO_2$ ,  $OCS$ , and allotropes of  $S$ ) is enormous: At least 1000 times greater than any plausible surface source or sink [5]. All these potential atmospheric and surface reactions involving sulfur make the sulfur cycle on Venus complex, but they also hold the promise that sulfur itself may be a key marker of recent changes in Venus' climate.

**Detecting Climate Change with New Missions to Venus:** New missions to the surface of Venus will make it possible to soon test hypotheses about the current rate of volcanism on Venus, the longevity of its clouds, and to test for epochs of recent climate change [7]. Isotopic ratio measurements of  $^{32}S/^{33}S/^{34}S$  within  $SO_2$  and  $OCS$  can definitively say whether all  $S$  has undergone mass independent fractionation, and hence was derived exclusively from photochemistry in the upper atmosphere. Landed imagery, at resolutions 5-10 times better than the spectacular Venera 14 images (Fig 3), and at a range of carefully selected colors, can look for layering and compositional changes indicative of climate change. Changes in diffusive regime, and hence climate and chemistry, can be detected by elemental, chemical, and mineralogical analysis of material from the surface and from a few cm below the surface. Finally, the exciting opportunities to map the surface in 3 narrow windows near  $1 \mu m$  hold the promise to discriminate compositional and hence possible weathering history changes in different terrains.



**Figure 3.** Surface image of Venus from Venera 14. Layered slabs are evident, with layers on scales of cm.

[1] Fegley, B. and R.G. Prinn (1989) *Nature* 337, 55-58. [2] Bullock, M.A. and D.H. Grinspoon (2001) *Icarus* 150, 19-37. [3] Bullock, M.A., D.H. Grinspoon, and J.W. Head (1993) *GRL* 20, 2147-2150. [4] Bertaux, J.L., et al. (1996) *JGR* 101, 12,709-12,745. [5] Yung, Y.L. and M. Liang (2008) *B.A.A.S.* 40, Abstract 62.05. [6] Fegley, B., et al. (1997) in *Venus II*, University of Arizona Press, 591-636. [7] Bullock, M.A., et al. (2008) *B.A.A.S.* 40 Abstract 32.08.

**VENUS GEOCHEMICAL ANALYSIS BY REMOTE RAMAN – LASER INDUCED BREAKDOWN SPECTROSCOPY (Raman-LIBS).** S. M. Clegg<sup>1</sup>, J. E. Barefield<sup>1</sup>, R. C. Wiens<sup>1</sup>, C. R. Quick<sup>1</sup>, S. K. Sharma<sup>2</sup>, A. K. Misra<sup>2</sup>, M. D. Dyar<sup>3</sup>, M. C. McCanta<sup>4</sup>, and L. Elkins-Tanton<sup>5</sup>, <sup>1</sup>Los Alamos National Laboratory, P.O. Box 1663 MS J565, Los Alamos, NM 87545, sclegg@lanl.gov, jbarefield@lanl.gov, rwiens@lanl.gov, quick@lanl.gov, <sup>2</sup>Hawaii Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Rd., Honolulu, HI, 96822, sksharma@soest.hawaii.edu, anupam@hawaii.edu. <sup>3</sup>Dept. of Astronomy, Mt. Holyoke College, South Hadley, MA 01075, mdyar@mtholyoke.edu. <sup>4</sup>Dept. of Geology, Tufts University, Lane Hall, Medford, MA 02155, molly.mccanta@tufts.edu, <sup>5</sup>Massachusetts Institute of Technology, Dept. of Earth, Atmospheric and Planetary Sciences, Cambridge MA, 02139, ltelkins@mit.edu.

**Introduction:** The extreme Venus surface temperature (740K) and atmospheric pressure (93 atm) creates a challenging environment for future lander missions. The scientific investigations capable of Venus geochemical observations must be completed within several hours of the landing before the lander will be overcome by the harsh atmosphere. A combined remote Raman – LIBS (Laser Induced Breakdown Spectroscopy) instrument is capable of accomplishing the geochemical science goals without the risks associated with collecting samples and bringing them into the lander. Wiens et al. [1] and Sharma et al. [2] have demonstrated that one can integrate both analytical techniques into a single instrument capable of planetary missions. The goal of this abstract is to demonstrate that remote Raman – LIBS spectra can be acquired under Venus conditions to yield quantitative geochemistry on Venus-analog rocks.

**Experimental:** The LIBS experiments involve focusing a Nd:YAG laser (1064nm, 10Hz, 50mJ/pulse) onto the surface of the sample. The laser ablates material from the surface generating an expanding plasma containing electronically excited atoms, ions and small molecules. The excited species emit light at wavelengths diagnostic of the species present in the sample as they relax to lower electronic states. Some of this emission is collected with a telescope and directed into a solarization resistant fiber connected to a dispersive spectrometer. The samples are placed 1.67m from the telescope in a cell filled with 93atm of supercritical CO<sub>2</sub> at 423K, a temperature much lower than the 740K Venus surface temperature.

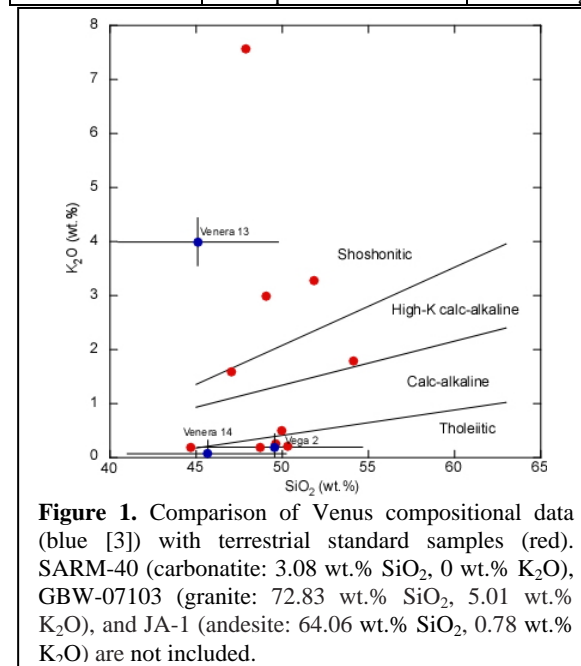
The Raman experiments employed a Nd:YAG pulse laser operating at 20 Hz and with a maximum pulse energy of 35mJ/pulse at 532nm. A 5x beam expander was used to focus the 532 nm laser beams onto the sample at 9 m from the beam expander.

**Sample Selection:** Our knowledge of the surface composition of Venus is limited. The most complete data available come from Soviet Venera and VEGA landers. Data from all landers suggest a surface composition that is primarily basaltic [3], although care

must be taken when interpreting the data due to their imprecise nature resulting in large error bars.

**Table 1. Samples Studied**

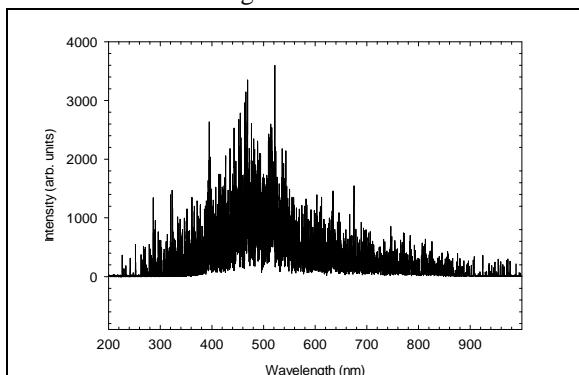
Sample	Rock Type	Source
TAP-04	olivine minette	[4]
BHVO-2	Hawaiian basalt	USGS
BCR-1	Columbia river basalt	USGS
GBW-07105	Olivine basalt	NRCCRM, China
GUW BM	Basalt	Brammer
JA-1	Japan andesite	GS Japan
SARM-40	Carbonatite	Mintek
GBW-07103	granite	NRCCRM, China
KV04-17	Kauai volcanics	M. Rhodes
KV04-25	Kauai volcanics	M. Rhodes
Liwi Liwi creek	Phillipines shoshonite	P. Hollings



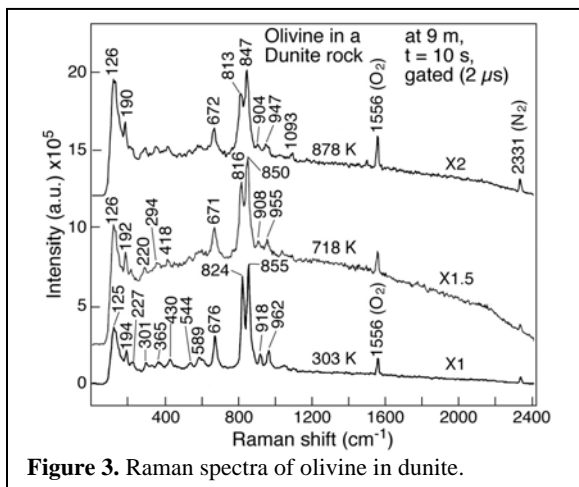
**Figure 1.** Comparison of Venus compositional data (blue [3]) with terrestrial standard samples (red). SARM-40 (carbonatite: 3.08 wt.% SiO<sub>2</sub>, 0 wt.% K<sub>2</sub>O), GBW-07103 (granite: 72.83 wt.% SiO<sub>2</sub>, 5.01 wt.% K<sub>2</sub>O), and JA-1 (andesite: 64.06 wt.% SiO<sub>2</sub>, 0.78 wt.% K<sub>2</sub>O) are not included.

The majority of the sampled material falls in the tholeiitic basalt region on an SiO<sub>2</sub>-K<sub>2</sub>O plot (Fig. 1), with some potentially more calc-alkaline material. However, rocks at both the Venera 8 and 13 landing

sites exhibited very high  $K_2O$  contents ( $\sim 4\%$   $K_2O$ ), consistent with a shoshonite classification. Due to these observed compositional differences and with the recognition of the imprecise nature of the current data, a range of igneous rock types has been chosen for study. Emphasis is placed on basaltic materials based on the Venera and Vega data.



**Figure 2.** LIBS spectrum of TAP-04.



**Figure 3.** Raman spectra of olivine in dunite.

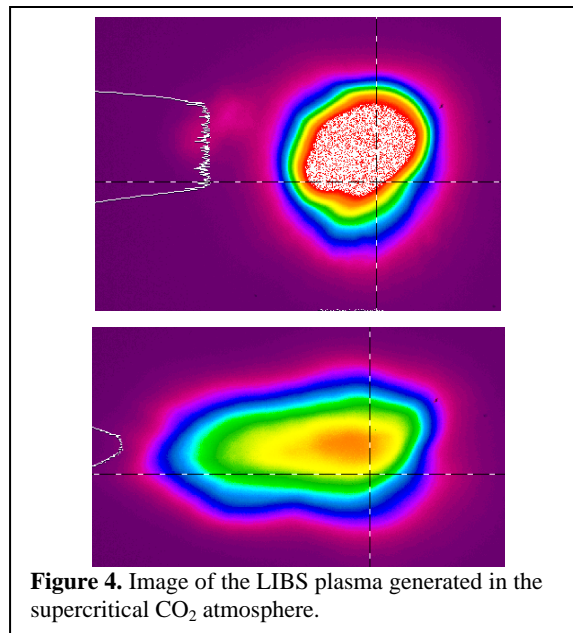
**Results and Discussion: LIBS Geochemical Analysis:** LIBS is fundamentally a geochemical analysis tool sensitive to the elemental composition of the sample. The challenge associated with LIBS geochemical analysis under Venus surface conditions involves overcoming the high surface pressure and generating the plasma. The collisions between the expanding plasma and the supercritical  $CO_2$  results in the deactivation of electronic states (lower total signal intensity) as well as the appearance of emission lines not typically observed under terrestrial conditions. The resulting spectra are much more spectrally complex (Fig. 2) but many of the typically diagnostic peaks are still observed.

**Raman Mineralogical Analysis:** Raman spectroscopy is fundamentally sensitive to the molecular signatures present from the sample. Fig. 3 shows the spectrum of olivine in dunite at 303K, 718K, and 878K.

The challenge to probing samples with Raman spectroscopy under Venus surface conditions is associated with the surface temperature (740K) and the associated blackbody radiation. The spectra depicted in Fig. 3 demonstrate that most of the Raman spectral features are observed with a properly gated spectrometer and a pulsed laser.

#### *Optical Transmission through Venus Atmosphere.*

Directing and focusing the laser from a cool Venus lander through a window and into the targeted sample was certainly a concern. Fig. 4 contains the images of the laser plasma generated with the LIBS laser focused to  $\sim 250\mu m$  diameter. The top image is the plasma (saturated intensity) under terrestrial conditions and the bottom image is the plasma under 93atm supercritical  $CO_2$  at 423K. The image of the plasma is clearly distorted by the presence of the  $CO_2$  but the peak intensity has not moved. The distortion could be due to the pressure on the window or due to the orientation of the sample and is under investigation.



**Figure 4.** Image of the LIBS plasma generated in the supercritical  $CO_2$  atmosphere.

**References:** [1] Wiens R.C., et al. (2005) *Spectrochim. Acta A* **61**, 2324-2334 [2] Sharma, S. K. et al. (2007) *Spectrochim. Acta A*, **68**, 1036-1045 (2007); [3] Barsukov VL (1992) Venusian Igneous Rocks. In Venus Geology, Geochemistry, and Geophysics (eds. VL Barsukov, AT Basilevsky, VP Volkov, and VW Zharkov). Univ. Arizona Press, pp. 165-176. [4] Richter K. and Rosas-Elguera J. (2001) *J. Petrol.*, **42**, 2333-2361.

**Acknowledgments:** We are grateful to Allan Treiman and Kevin Richter for sample selection discussions and to Kevin Richter, Michael Rhodes, Mac Rutherford, and Peter Hollings for providing samples.



**MAGMATISM ON VENUS: UPSIDE-DOWN MELTING IN GRAVITATIONAL INSTABILITIES AND A POSSIBLE ANALOG IN THE SIBERIAN LARGE IGNEOUS PROVINCE.** L. T. Elkins-Tanton<sup>1</sup> and S. E. Smrekar<sup>2</sup>, <sup>1</sup>MIT, Cambridge MA, LTELKINS@mit.edu, <sup>2</sup>Jet Propulsion Laboratory, Pasadena CA, suzanne.e.smrekar@nasa.gov.

**Introduction:** On Earth magmatism occurs on continents in the absence of subduction, often producing volatile-rich magmas such as those in the Leucite Hills, the Sierra Nevada, and Peru's Altiplano [1]. The primary hypothesis to explain this volcanism is foundering of the lower lithosphere into the mantle. The surface of Venus displays volcanic features indicating eruption of lavas with a wide range of viscosities, and its apparent one-plate structure is best compared to these continental settings on Earth.

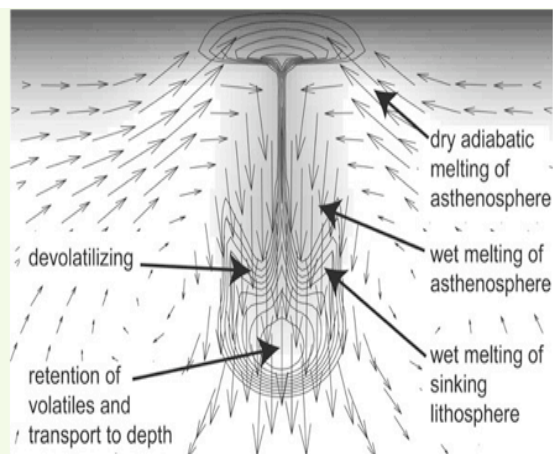
Parmentier and Hess [2] suggest that Venus has undergone cyclic catastrophic crustal recycling through gravitational instability. Both Dupeyrat and Sotin [3] and Hoogenboom and Houseman [4] suggest that eclogitization of the lower lithosphere can be a driving force for gravitational instabilities sinking from the lithosphere, the same process that has been invoked on Earth [1, 5, 6]. Instabilities may also be coupled with rising plumes [2-4, 7], which may provide both the source of the eclogitization and heat to promote ductile flow.

**Upside-down melting:** A gravitational instability forms when a perturbation in an internal planetary boundary grows through lateral flow. The material begins to sink into the underlying mantle material as a drip, exactly analogous to but reversed in the sense of growth from an ascending plume head. The unstable material will sink more rapidly than lateral flow in the lower lithosphere can feed it, resulting in an annulus of thinned lithosphere centered on the instability. Thus no dome forms in the lower lithosphere during ductile delamination. Traditionally magmatism associated with instabilities has been attributed to return flow of the asthenosphere into such a dome, but maintaining a dome in the lithosphere requires unusual rheological conditions not expected in such a setting [8].

This loss of the lower lithosphere is hypothesized to occur in response to a density contrast that may be caused by intruding mantle melts that freeze as eclogites. This mechanism requires no specific structural weakness beyond a dense region in the lithosphere that is gravitationally unstable with respect to the underlying mantle and that possesses a rheology conducive to flow. Density contrasts of as little as 1% are fully sufficient to drive gravitational instabilities.

Any volatile content in the sinking material may act in petrologically significant ways. The sinking lower lithosphere on Earth may contain 0.1 to 0.2 mass% of water even if only nominally anhydrous

minerals are present. The sinking lithospheric material heats conductively as it is surrounded by hot asthenosphere. Depending upon its rate of descent and volatile content, the sinking material may (1) devolatilize (as a descending slab in a subduction zone does), (2) carry volatiles to depth, sinking in some cases faster than slabs and thus carrying volatiles to depth more efficiently, or (3) heat sufficiently quickly to cross its solidus and itself produce magma. Because this melting in instabilities would occur as they sink, we have termed this novel melting mechanism "upside-down melting" [8] (Figure 1).



**Figure 1:** Schematic of a gravitationally-driven drip with the melting and volatile transport potentials marked. Here "wet" melting can mean melting caused by any slight incompatible element increase, for example, by an excess of potassium or carbon.

**Models for Venus:** We presented numerical experiments showing that lithospheric gravitational instabilities can produce lavas with compositions consistent with the range of volcanic forms seen on Venus in Elkins-Tanton et al. [9]. The existence of incompatible elements and their oxides (specifically, water, carbon, sulfur, and alkali elements) in even trace-level concentrations in the Venusian mantle allow the formation of a variety of magmatic source regions. The pressure and temperature paths that the dense lithospheric materials travel as they sink into the Venusian mantle indicate that the lithospheric material may devolatilize as it sinks, enriching the surrounding upper mantle, or it may itself melt [8,9].

The physical and chemical processes associated with gravitationally-driven sinking plumes can produce

magmas with a variety of compositions and viscosities, potentially consistent with the range of Venusian volcanic forms. These models predict melting in a range of source compositions in the absence of plate tectonics, creating both basaltic magmas and magmas with higher levels of incompatible elements, including alkalis and low amounts of volatiles (consistent with the suggestions of McKenzie et al. [10]).

These processes also suggests that Venus may recycle incompatible elements internally. Indeed, if Venus began with an internal volatile content, then no amount of partial melting can make it entirely volatile-free even in the absence of recycling into the interior. These models therefore suggest geodynamic processes that can produce a range of magmatic activity and retain some interior volatiles on a one-plate planet. Up-side-down melting on a one-plate planet may also provide some continuous, if minimal, contributions to the planetary atmosphere.

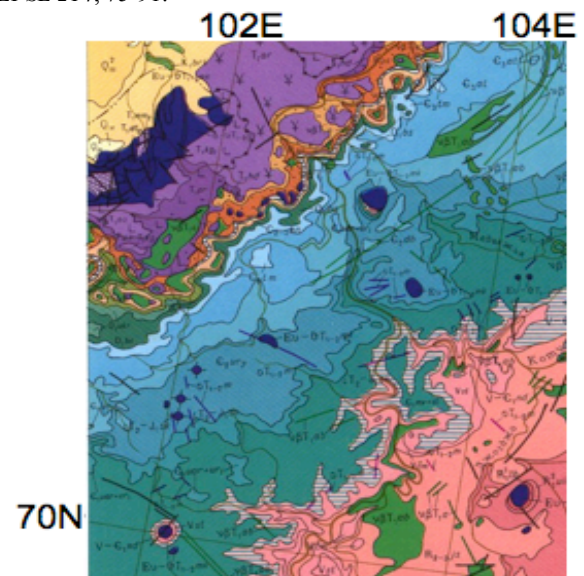
**Earth analog?** The compositions of Venusian lavas and the processes that create them on an apparently one-plate planet remain open questions. On the Earth, the best-understood volcanic processes operate at mid-ocean ridges and at volcanic arcs, both of which are the result of Earth's apparently unique plate tectonics. On Venus, a similar or even larger range of magmatic viscosities appears to be produced in the absence of plate tectonics. On Earth, the closest analog is volcanism on stable cratons, such as is seen in Siberia in the form of flood basalts, kimberlites, and carbonatite complexes [e.g. 11,12].

In the summer of 2008 Elkins-Tanton and a team of scientists visited the Guli alkaline intrusion in Arctic Siberia. This 1500 to 1800 km<sup>2</sup> igneous complex [13] consists of concentric rings of the following lithologies, starting from the center: Calcic carbonatites, magnesian carbonatites, highly metasomatized lavas (largely converted to phlogopite), alkaline lavas, and dunites and pyroxenites. The complex is certainly eroded but still indicates that deep rocks were brought up and that some violent eruptions may have occurred; the compositions are conspicuously volatile-rich.

Similar centers occur on a fairly regular spacing and may have been drips triggered by the hot plume (Fig. 2). Their lithology and deep structure may be revealed by their gravity signature: by far the highest amplitude gravity anomaly in the region is located over the Guli, with lesser gravity anomalies over the other alkaline provinces [Bradford Hager, personal communication]. This gravity anomaly has no significant topographic counterpart, suggesting that deep structure, perhaps a thin lithosphere with near-surface mantle materials, causes this anomaly.

Preliminary ages obtained from Guli rocks [14] indicate it is slightly younger than the bulk of the Siberian flood basalts, which are widely thought to have been caused by a plume. Thus intrusion of melt from the plume may have created a dense, unstable lithosphere, triggering drip formation at the lithosphere-aesthenosphere interface, and producing magmatism. Continuing studies of the compositions and structures of these Siberian alkaline provinces should inform whether or not they are consistent with gravitational instabilities, and thus may strengthen their parallel to structures and processes on Venus.

**References:** [1] Kay R.W. and S.M. Kay (1993) *Tectonophysics* 219, 177-189. [2] Parmentier E.M. and P.C. Hess (1992) *GRL* 19, 2015-2018. [3] Dupeyrat L. and C. Sotin (1995) *Planet. Sp. Sci.* 43, 909-991. [4] Hoogenboom T. and G.A. Houseman (2005) *Icarus* 180, 292-307. [5] Schott, B., and H. Schmeling (1998) *Tectonophysics* 296, 225-247. [6] Elkins Tanton L.T. and B.H. Hager (2000) *GRL* 27, 3937-3940. [7] Smrekar S. E. and E. R. Stofan (1997) *Science* 277, 1289-1294. [8] Elkins-Tanton, L.T. (2007) *JGR* 112, B03405. [9] Elkins-Tanton L.T. et al. (2007) *JGR* 112, E04S06. [10] McKenzie D. et al. (1992) *JGR* 97, 15967-15976. [11] Fedorenko V.A. and G.K. Czamanske (1997) *Int'l Geo. Rev.* 39, 479-531. [12] Boyd F.R. et al. (1997) *CMP* 128, 228-246. [13] Vasiliev Y.R. and V.V. Zolotukhin (1995) *Episodes* 18, 155-164. [14] Kamo S.L. et al. (2003) *EPSL* 214, 75-91.



**Figure 2.** Alkaline complexes in dark blue, showing extent and spacing, in Arctic Siberia. All associated in time with the Siberian flood basalts and thus presumably with their plume formation. Flood basalts themselves in purple. Detail from *Geological Map of the Siberian Platform* (1999).

## Magmatic Diversity on Venus: Constraints from terrestrial analog experiments.

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Igneous diversity is common on terrestrial planets. This diversity has been experimentally investigated for terrestrial [1-6] and martian basalts [7-10], but only suggested for Venus [11, 12]. Since Venus and Earth are sister planets and have similar bulk chemistry [13, 14], experiments on terrestrial basalts can place constraints on the formation of the Venera and Vega basalts. Furthermore, experimental results can suggest the types of basalts that should be present on Venus if processes of differentiation similar to the Earth are occurring on Venus, as suggested by the Venera and Vega analyses (Table 1). Results from these experiments can constrain the type and quality of data needed from future missions to determine the petrologic history of surface igneous rocks.

**Introduction:** Extensive work has been done on exploring the data from the Venera and Vega missions (see summaries in [13, 15]). This work has shown that Venus and Earth have similar K/Th, U/Th, and K/U ratios and in general are sister planets with similar chemistry [13, 14]. The Venera 13 analysis is consistent with that of a leucitic basalt, while the Venera 14 and Vega 2 analyses are similar those of olivine tholeiites from mid-ocean ridges [e.g. 15]. Extensive experimental work has been conducted on a terrestrial olivine tholeiite at varying pressures, temperatures, and water contents in order to understand the residual liquids that could be produced by igneous differentiation [1-6]. If similar processes of magma ponding and differentiation were occurring on Venus, then compositions similar to terrestrial igneous suites would be expected. Therefore, these experimental results can constrain the types of igneous suites that could be present and the quality of data needed from future missions to distinguish the different suites.

**Experiments on Terrestrial Analogs:** Experiments have been conducted on terrestrial tholeiitic basalts at varying pressures and water contents to explore the compositions of rocks that can be produced by igneous differentiation [1-6]. Igneous differentiation occurs when a magma ponds and a certain depth, cools and crystallizes. The residual liquids then separate from the crystallized minerals and erupt on the surface. The residual liquids produced by differentiation in these experiments range from rhyolites to phonolites, depending on pressure of fractionation and bulk volatile content. Table 1 summarizes the experimental conditions (P, volatile content) needed to produce each terrestrial basalt suite. Figure 1 shows the compositional diversity that can be produced by fractionation at varying depths and water contents.

*Surface:* Fractionation at low pressure (< 2kb) produces residual liquids that follow the tholeiitic trend, for example the igneous suite of Volcano Alcedo, Galapagos and Thingmuli, Iceland [6]. These suite include olivine tholeiites, ferrobasalts, icelandites, and rhyolites [16-18].

*Upper Mantle:* Ponding at the base of the crust/upper mantle can produce three different igneous trends, depending on pressure and volatile content. At 5-11kb and relatively anhydrous conditions, fractionation of olivine tholeiite yields a potassic silica-saturated alkalic suite, similar to that of the Craters of the Moon [2, 3]. The suite consists of jotunites, ferrodiorites, trachybasalts, monzonites, syenites, and potassic rhyolites [19-21]. At slightly greater pressures and higher water contents (9-11kb and >0.3 wt% H<sub>2</sub>O), fractionation of the olivine tholeiite produces a sodic alkalic trend, such as are found on Ascension Island and the Nandewar Volcano [4]. These suites

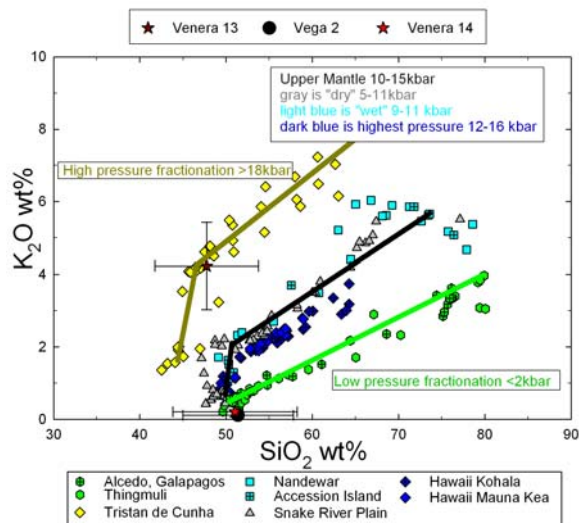
Fractionation Pressure		Volatile Content	Trend	Terrestrial Analog
Surface	0-2kb		Tholeiitic Trend	Galapagos Thingmuli
Base of the crust/Upper mantle	5-11kb	<0.3wt% water	Potassic Alkalic Series	Snake River Plain
	9-11kb	>0.3wt% water	Sodic Alkalic Series	Nandewar Ascension Island
	12-16kb	>0.3wt% water	Silica-undersaturated	Hawaii
Mantle	18-27kb	~0.2 wt% water	Phonolitic Series	Tristan de Cunha

**Table 1.** Experimental conditions (pressure and water content) of magma ponding and fractionation to produce 5 terrestrial igneous suites [1-6]. Examples of each terrestrial igneous suite are include and are possible analogs to Venus igneous suites (and possibly volcanoes). Color coded the same as Figure 1.



include alkali-basalts, hawaiites, mugearites, benmoreites, trachytes, and rhyolites [22, 23]. At even greater pressures (18-27kb), fractionation of that same olivine tholeiite produces silica-undersaturated rocks like those of the Kohala and Mauna Kea volcanoes of Hawai'i [5]. These rocks consist of alkali-basalts, nepheline-hawaiites, nepheline-mugearites, and phonolites [24-27].

**Mantle:** At greater depths within the mantle, fractionation of the olivine tholeiite produces a phonolitic series, like that of Tristan de Cunha [1]. This suite includes lavas like alkali-picrite, olivine-basanite, olivine-nephelinite, and mellite-nephelinite [28].



**Figure 1** K<sub>2</sub>O vs. SiO<sub>2</sub> showing trends found in terrestrial intra-plate suites and their conditions of formation [1-6]. Modified after [9, 29]. References for rocks and fractionation conditions are within the text. Venera and Vega analysis include 2 sigma error [13]. All data re-normalized to 100 wt% without sodium or phosphorous to be able to directly compare terrestrial rocks with the Venera and Vega data.

**Venus basalts:** Figure 1 compares the compositional diversity of terrestrial magmatic suites with the Venera 13, 14 and Vega 2 data. The results shown here suggest that Venera 14 and Vega 2 basalts are comparable with an olivine-tholeiite from a continental or ocean island hotspot. Olivine-tholeiitic compositions on Earth can be produced at pressures less than 18kb and various water contents [1]. This suggests an upper mantle origin for the Venera 14 and Vega 2 basalts; more precise analyses are needed to fully constrain the depths of formation and water contents of the Venus basalts.

The Venera 13 analysis is comparable with a silica-undersaturated rock (possibly a basanite or nephelinite). This suggests a deeper origin than the Venera 14 and Vega 2 basalts. If the Venera 13 basalt formed in similar ways to terrestrial basalts then it formed at rela-

tively high pressure (>18 kbar) and from a hydrous source region (~0.2 wt% bulk water in the basalt). However, more precise and complete analyses, including mineralogy and abundances of Na, Cr, and P, are needed to fully understand the origin of these K-rich basalts.

**Summary:** Extensive experimental work on terrestrial olivine-tholeiite compositions demonstrate that simple igneous fractionation can produce a wide range of igneous compositions from a single magma type. Analyses of surface materials from the Venera and Vega landers suggest that Venus' lavas include olivine tholeiites and silica-undersaturated compositions. This suggests that Venus igneous rocks maybe as compositionally diverse as those found on the Earth. Future missions that provide high precision bulk chemical analysis of igneous rocks, and surface chemistry, can constrain the diversity of the Venus surface and explore if Venus truly is our sister planet.

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**TESSERA TERRAIN IS A FUNDAMENTAL GEOCHEMICAL TARGET.** M. S. Gilmore, Dept. of Earth and Environmental Sciences, Wesleyan University, 265 Church St., Middletown, CT 06459, mgilmore@wesleyan.edu.

**Introduction:** Venus tessera terrain is characterized by complex deformation comprising at least two sets of intersecting ridges and grooves which contribute to high radar backscatter [1,2]. Tessera terrain is a major tectonic unit on Venus, comprising ~8% of the surface of the planet and occurring as both large ( $>10^3$  km across) high-standing (~1-4 km above mean planetary radius (MPR = 6051.84 km)) plateaus and small ( $<100$  km across) outcrops scattered among the global volcanic (presumably basaltic) plains at low elevations [3]. Stratigraphic studies of tessera terrain establish that they are generally embayed by plains materials [1,3,4-8], however, the density of craters on both terrains is similar where the tesserae yield a surface crater retention age of 1X [9] to 1.4X [10] the average age of the surface of ~300 [11] to ~800 Ma [12]. The apparent spatial randomness of the crater population on the surface of Venus and rarity of volcanically embayed craters [13, 14] can be produced by a geologically rapid emplacement of that surface (e.g., 14,15), provoking several theories of catastrophic formation of the crust by varying methods (e.g., 16-18). Alternatively, the crater record has been modeled to result from steady state geologic processes that are a consequence of secular cooling of the planet [13,19-21]. In either case, tesserae are interpreted to be remnants of an extinct pre-plains era in venusian geologic history. Several lines of evidence support the hypothesis that this era was characterized by higher strain rates and a thinner lithosphere than at present. Shallow apparent depths of compensation measured at tessera plateaus indicate that presently they are regions of thickened crust and are not dynamically supported, consistent with an extinct deformation episode (e.g., 22-25). Studies of the characteristic wavelengths of structures in tessera terrain are similar from region to region [26,27] and can be attributed to a (likely global) lithosphere thinner than that estimated today [28]. Lastly, observations of the deformation and preservation of impact craters yield strain rate estimates for the tesserae 1-2 orders of magnitude greater than at present [29]. Analyses of crater deformation on tessera terrain constrain this decline in surface strain rates to a geologically short period of time of approximately 10% of the average crater retention age of the surface [30,31].

Tessera terrain thus uniquely records the geologic history of an ancient Venus prior to and during plains emplacement.

**Are Tesserae Granitic?:** The D/H ratio of the venusian atmosphere is ~150X the terrestrial value, indicating that Venus has lost water over its history [32]. Thus it is conceivable that water was incorporated into

magmatic processes in the early history of Venus fostering magmatic differentiation and the production of silicic compositions. As none of the Venera landers sampled tessera terrain, we have only indirect evidence consistent with more evolved compositions for tessera terrain.

Hashimoto et al. [33] used emission at 1 micron measured by the Galileo spacecraft and found differences between tessera highlands and plains that can be explained by composition. This method exploits the relatively low emissivity of common felsic minerals with respect to common mafic minerals.

Romero and Turcotte [34] argue that the preservation of tessera terrain throughout an era of plate tectonics is made possible because it comprises buoyant, low density crust of differentiated compositions. This model provides a mechanism whereby tesserae may be preserved for billions of years.

A granitic composition for Venus tessera terrain would constrain our understanding of the inventory and history of water on the planet and may likely require subduction for formation. Dating granitic rocks would place the water inventory in a temporal context.

#### **Strategies for Geochemical Measurement of Tesserae:**

*Landing Site Selection.* Although craters constrain the the most recent tessera deformation to ~ the mean surface age of the planet, there may be variability in the relative ages of domains within tessera terrain. Tessera terrain includes a variety of structural fabrics, which have been classified and interpreted by a number of workers [5, 35, 36]. For example, the central regions of several large tessera plateaus exhibits a fabric with numerous structures oriented ~ orthogonally. Plateau margins typically exhibit margin-parallel structures (commonly folds). The several models proposed for tessera formation predict different stratigraphic relationships between these central and marginal facies [5, 35, 36]. Mapping of Ovda and Tellus Regio identify multiple tessera domains that are interpreted to have assembled together during a collisional event [37, 38]. In the case of Tellus, it appears that plains materials are deformed and incorporated into the tessera [38]. Detailed stratigraphic mapping of tesserae is necessary for judicious landing site selection, particularly if the goal is to access the oldest and most silicic materials.

*Reflectance Spectroscopy.* Several workers have utilized the atmospheric window at 1 micron to measure surface emissivity from orbit [e.g., 33, 39]. A difficulty with this measurement is the proper accounting

of the Venus cloud structure and composition. Measurements of 1 micron emissivity from balloon would likely constrain this problem. Such data can theoretically be used to measure differences in mineral emissivity that is related to composition [e.g., 33].

Any measurements of surface reflectance from orbit to ground require a good understanding of the weathered surface of Venus, where atmospheric surface interactions are predicted to produce a wide variety of (anhydrous) metamorphosed compositions [e.g., 40], which may be occurring in an oxidizing environment [41]. The high temperatures at the Venus surface are also predicted to cause spectral absorptions to broaden and shift toward longer wavelengths. It remains to be seen if materials that have discernable emissivities in current spectral libraries would maintain their spectral contrast in the Venus environment.

*In Situ Measurements.* Weathering rates and products are also essential to both our ability to interpret Venus geochemical data collected in situ and as a constraint on mission design (e.g., requirements for drilling). Laboratory chemical weathering rates can be estimated for specific mineral systems [e.g. 40]. Physical weathering rates of basalt surfaces are estimated to be  $\sim 10^{-3} \mu\text{m yr}^{-1}$  [42], yielding a 30-50 cm regolith over 300- 500 Ma. SAR backscatter data liken some tessera surfaces to terrestrial a'a flows [43].

*Sample Return.* Sample return from Venus is critical to placing the planet in its geochemical context within the solar system and is likely required for radiometric age dating (for systems that are closed at Venus surface temperatures, e.g., U/Pb, Rb/Sr, Sm/Nd, NOT K/Ar). Because of their stratigraphic position, tessera are the most likely surface materials to include ancient (Ga) rocks. It is possible that the tessera are themselves ancient, and preserved through time as suggested by [34]. It is also possible that the tesserae contain ancient minerals that have survived deformation and metamorphism. This is the case on Earth, where Pre-Cambrian zircons ( $\text{ZrSiO}_4$ ) persist in rocks of various ages. As in the terrestrial case, analysis of Venus zircons would critically constrain our understanding of the history of water on the planet. For Earth, Eiler [44] has shown that the interaction of rocks with water at low temperatures results in elevated  $\text{d}^{18}\text{O}$  values that contribute to elevated  $\text{d}^{18}\text{O}$  values of granites that incorporate these water-rich rocks. Zircons from these granites retain this heavy oxygen signature and have been used to support the existence of continental crust, oceans and plate recycling in the Hadean [45]. Analyses of minerals trapped in zircons may also constrain the heat flow during the Hadean [46]. Estimates of the # of zircons in a given volume of rock may constrain sample return volumes; if 100

grams of sample should yield 100s of zircons, even for basalt  $\rightarrow$  30  $\text{cm}^3$  drill core.

**Conclusion:** Tesserae are the oldest materials exposed on the surface and are the best candidates for containing ancient (Ga) rocks and for comprising evolved compositions. Tessera plateaus may contain regions of varying age, which can be constrained by geologic mapping. Surface composition may be assessed via remote or in situ spectroscopy and by direct measurement from a lander or vis sample return. The interpretation of in situ analyses require a better understanding of the expected weathering products at the surface of Venus and may constrain sampling strategy. Tessera roughness will constrain landing site safety and sample access. Sample return is critical for age dating and for detailed analyses that can constrain the history of water and nature of tectonism on Venus through time. I recommend that we consider the collection and preservation of zircons as a high priority for sample return.

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**MAGNETOTELLURIC SOUNDING OF THE INTERIOR OF VENUS.** R. E. Grimm<sup>1</sup> and G. T. Delory<sup>2</sup>,  
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**Introduction.** Electromagnetic (EM) sounding has been widely used to reveal earth structure from depths of meters to hundreds of kilometers [e.g. 1-5] and has also probed the deep interiors of the Moon [e.g. 6-9] and the Galilean satellites [10]. The magnetotelluric method [MT: 11,12] enables natural-source soundings from a single platform, without any external measurements or prior knowledge as was required for previous planetary EM applications. MT can in principle be performed anywhere within about 1 skin depth of the target, allowing measurements from the ground, the air, or in space (as long as the last is within any shielding ionosphere or current sheath). For Venus, MT measurements from the surface or an aerial platform can reveal lithospheric and crustal structure, providing key constraints on thermal and geodynamic evolution.

**Terrestrial and Planetary EM Sounding.** Time-varying natural or artificial EM source fields induce eddy currents in planetary interiors, whose secondary EM fields are detected at or above the surface. These secondary fields shield the deeper interior according to the skin-depth effect, so that EM fields fall to  $1/e$  amplitude over depth  $\delta$  (km) =  $0.5\sqrt{\rho/f}$ , where  $\rho$  is the resistivity and  $f$  is the frequency. EM sounding exploits the skin-depth effect by using measurements over a range of frequency to reconstruct resistivity over a range of depth [2,11,12]. The EM response is often expressed as the apparent resistivity  $\rho_a$ , the resistivity of a halfspace giving the same signal as the structure under test. Alternative EM response parameters such as the impedance, admittance or the transfer function can also be expressed as  $\rho_a$  [9,11-13].

To date, planetary EM sounding has used one or more magnetometers by (1) a priori knowledge of the amplitude and phase of the source field, such as the time variation introduced by the motion of the Galilean satellites through Jupiter's main field [10], or (2) use of a second, distantly orbiting magnetometer to measure the source field, as was done using the Apollo 12 surface magnetometer and Explorer 35 spacecraft [6-9]. A single magnetometer is also sufficient at very low frequencies where the source wavelength can be specified (e.g., a diurnal variation) or where the target can be approximated as a perfect conductor.

**Magnetotelluric Method.** A classical EM-exploration approach offers a complete shallow-to-deep sounding from a single station, without specific knowledge of the source field. The *magnetotelluric method* (MT) uses orthogonal horizontal components of the local electric (E) and magnetic (H) fields to

form  $\rho_a = (1/\mu\omega)(E/H)^2$ , where  $\mu$  is the permittivity and  $\omega$  is the angular frequency [11,12]. At planetary scales, the MT plane-wave response can be transformed to spherical geometry [9,13]. At small scale, MT naturally provides spatially independent measurements with horizontal resolution comparable to the EM skin depth. Therefore a single station can determine global and local structure, and multiple and/or mobile stations can assess lateral heterogeneity.

Challenges associated with measurement and interpretation of the electric field include (1) Capacitive coupling of signals in regions of high resistivity; (2) Elimination of electrostatic effects from measurements made in plasmas; (3) Elimination of cross-contamination by high-amplitude vertical ("fair-weather") fields in planetary atmospheres, and (4) Erroneous "static shift" in  $\rho_a$  caused by spatial and temporal aliasing due to local conductors. Our PIDDP and MIDP programs have extended previous work in resistive environments [14] to develop high-impedance electrometers that enable capacitive measurements at low frequencies. Plasma effects can be assessed with a Langmuir probe and/or electrostatic analyzer. The time variation in vertical E-field is apparent in aerial surveys only and is largely due to measureable and modelable changes in platform attitude. Very large conductivity contrasts in the shallowest parts of the Earth that give rise to static shifts are not likely to be common in the resistive (cold and/or dry) outer portions of other solid bodies in the solar system. A mobile platform can average out static shift within the lateral footprint (again, about one skin depth).

**Data Processing and Interpretation.** Complex impedances, formed in the spectral domain using least squares, are transformed to the real quantities apparent resistivity and phase. Standard nonlinear inversions recover resistivity as a function of depth [11,12]. Because resistivity is a strong function of temperature, deep EM sounding is a window into thermal conditions of the interior and is a surrogate for heat flow [4,5]. Interconnected, conductive graphite or iron-bearing minerals can influence bulk EM properties in special environments, but in general the resistivity of terrestrial planet deep interiors is dominated by electron hopping introduced by trace quantities of trivalent cations (Al, Fe) and by proton hopping introduced by absorbed H<sub>2</sub>O [15-17].

**Venus Science.** EM sounding can address the following high-priority questions for Venus:

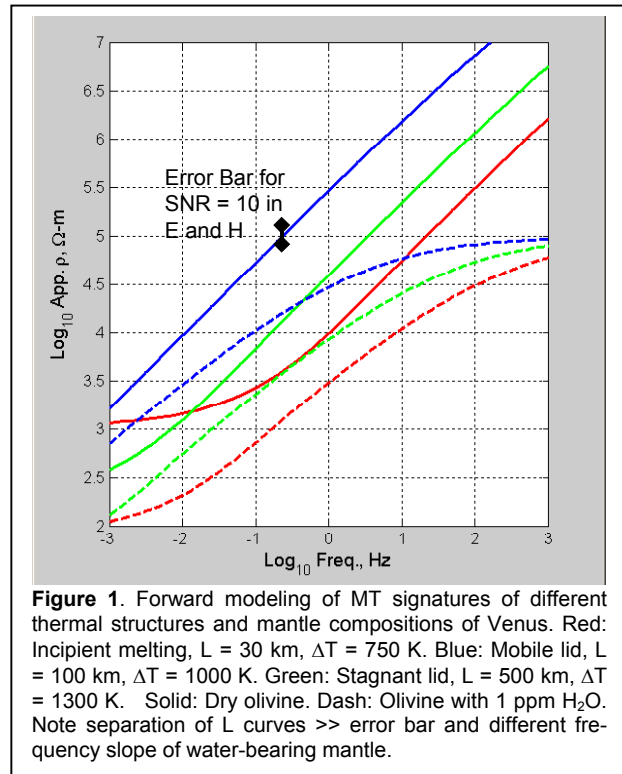
(1) *What is the thickness of the lithosphere?* Discounting a purely conductive-equilibrium endmember,

estimates of the asymptotic lithospheric thickness  $L_\infty$  vary from  $\sim 100$  km for a mobile convective lid to  $\sim 500$  km for a stagnant lid [18,19]. Determination of lithospheric thickness is pivotal to understanding how Venus loses its heat and hence understanding its geological history, particularly past and present tectonics and volcanism. Interior temperatures  $T$  and lithospheric thickness  $L$  can be constrained using laboratory data (Fig 1), as mentioned above. However, it is possible to determine  $L$  from just two measurement locations, without any supporting laboratory data, under the assumption that the topographic difference  $h_2 - h_1$  is purely due to lithospheric thermal isostasy. For a maximum EM penetration depth  $d$ , assume  $T(d) = \text{const}$  and  $dT/dz = \text{const}$  in the mantle lithosphere: therefore  $L_2/L_1 = d_2/d_1$ . But from isostasy,  $L_2 - L_1 = (h_2 - h_1)\rho_L/\Delta\rho$ , where  $\rho_L$  is the mean lithospheric density and  $\Delta\rho$  is the lithosphere-asthenosphere contrast. In practice, a least-squares solution involving all measurement locations would be performed, and the data should be restricted to lowlands where crustal-thickness variations are thought to be minimal [20]. Note that in neither approach does the EM sounding have to extend all the way through the lithosphere in order to determine its thickness.

(2) *What is the water content of the mantle?* The lower activation energy of hydrous olivine compared to dry olivine leads to a distinct slope in apparent resistivity vs. frequency (Fig. 1). Comparison with laboratory data [16] are necessary to quantify  $\text{H}_2\text{O}$  content, which should be resolvable at ppm levels and thence constrain degassing models [21].

(3) *What is the thickness of the crust?* The style of crustal accretion and destruction controls crustal thickness and composition [20]. Crustal thickness in non-highlands regions is thought to be relatively constant, but the mean value is still uncertain by up to a factor of 2 [20, 22]. Determination of crustal thickness in highlands can separate thermal/compositional isostasy [23].

**Venus Environment and Application.** Natural EM signals for Venus include solar-wind MHD oscillations  $<1$  Hz [24] and lightning  $>1$  Hz [25]. Electric fields are best measured at the surface, using long baselines from ballistic electrode deployment and exploiting partial galvanic coupling with the hot surface. Frequencies  $>10^{-2}$  Hz can be accurately characterized with a 1-hr lifetime. High-temperature magnetometer development is the critical path to surface measurements. Alternatively, in the benign environment at 50-60 km altitude, H-field measurements are simple but the E-field measurement is challenging due to the resistive atmosphere. For an aerial survey, the altitude must be less than  $\sim 1$  skin depth, so depths  $>50$  km could be targeted, but depths  $<50$  km would lie in a blind zone. Aerial measurements would therefore be



**Figure 1.** Forward modeling of MT signatures of different thermal structures and mantle compositions of Venus. Red: Incipient melting,  $L = 30$  km,  $\Delta T = 750$  K. Blue: Mobile lid,  $L = 100$  km,  $\Delta T = 1000$  K. Green: Stagnant lid,  $L = 500$  km,  $\Delta T = 1300$  K. Solid: Dry olivine. Dash: Olivine with 1 ppm  $\text{H}_2\text{O}$ . Note separation of L curves  $\gg$  error bar and different frequency slope of water-bearing mantle.

optimized for the mantle and able to detect only the thickest highlands crust. Long-lived, mobile measurements also offer the greatest data diversity, improving SNR and improving separation of the contributions of temperature and composition to subsurface resistivity.

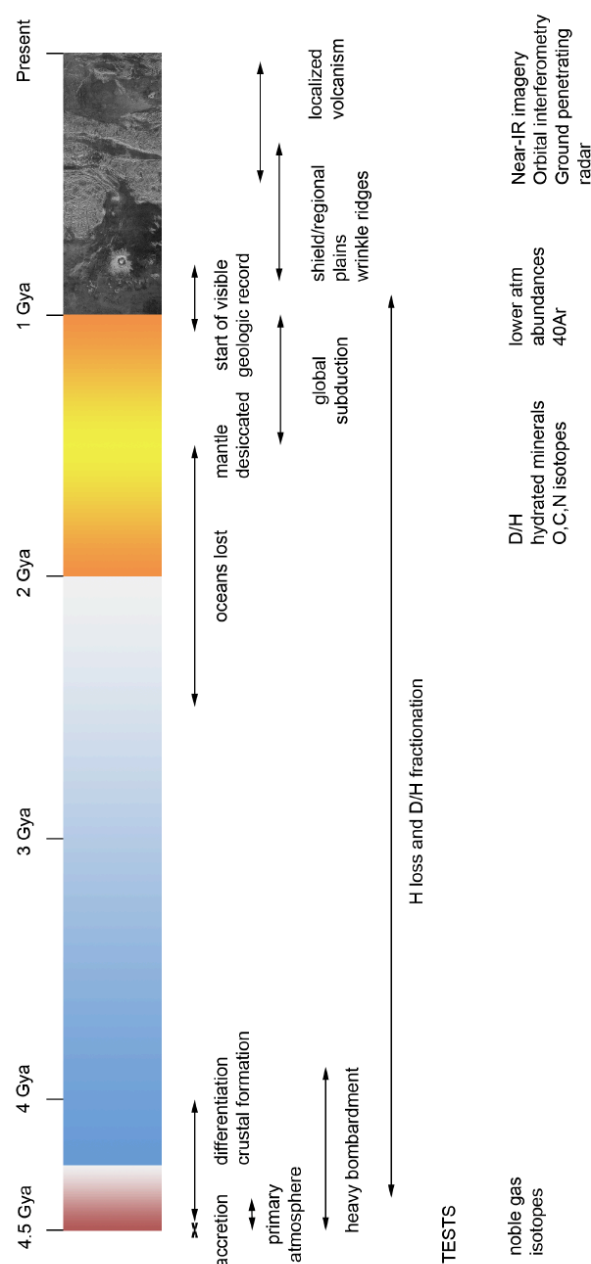
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**THE HISTORY OF VENUS.** David H. Grinspoon<sup>1</sup>, Mark A. Bullock<sup>2</sup> and James W. Head<sup>3</sup>, <sup>1</sup>Dept. of Space Sci., Denver Museum of Nature & Science, 2001 Colorado Blvd., Denver, CO 80205 ([dgrinspoon@dmns.org](mailto:dgrinspoon@dmns.org)), <sup>2</sup>Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302 ([bullock@boulder.swri.edu](mailto:bullock@boulder.swri.edu)), <sup>3</sup>Dept. of Geological Sci., Brown University, Providence, RI 02912 ([james\\_head@brown.edu](mailto:james_head@brown.edu)).

**Introduction:** Venus is commonly thought to have experienced a transition, within 1 billion years of its formation, to its current highly desiccated state from a wet, more Earth-like past [1]. The assumption of similar origins rests mostly upon cosmogonic arguments. However, it is possible that stochastic differences in the late phases of accretion could have left the “twin planets” with unequal volatile inventories [2] or very different amounts of volatile loss and interior processing through catastrophic early impacts [3-5]. Current estimates of the timescale for water loss are highly unconstrained, with error estimates larger than the age of the planet, due to the unknown effects of cloud-albedo feedback and other poorly understood complexities of a young, warm, watery Venus. While the deuterium-to-hydrogen ratio indicates that most of the source water for the current atmospheric inventory has escaped, it does not constrain the amount of primordial water [6,7]. Future measurements of rare gases and stable isotopes will allow more definitive constraints on early evolution and volatile abundances.

**The Geologic Record:** The geological record revealed by Magellan suggests another, more recent, global transition. A sparse, randomly distributed and relatively pristine crater population indicates a decrease in resurfacing rate between 300 and 1000 Myr ago [8-12], although the detailed time-history is poorly constrained and subject to debate. The accompanying decline in outgassing rate would have caused large climate changes [13]. These may have caused globally synchronous plains deformation [14] and other geologic signatures [15,16].

Grinspoon and Bullock [17] suggested that these two transitions have been part of a single planetary transformation. The loss of surface and atmospheric water through evaporation, photodissociation and H escape could have initiated changes in global convective style which led directly to the currently observed surface features. The shut-off of subducting hydrated sediments may have led to the desiccation of the mantle and consequent loss of an asthenosphere which would have facilitated the transition from plate tectonics to single plate behavior.



**Figure 1.** A timeline showing some possible stages in the history of Venus, and some tests that may help to confirm, refute or refine this story.

**A Common Story:** In this talk we will present the history of Venus, told as a sequence of evolutionary stages from formation to the present day. Of course, this story cannot really be told with our current level of knowledge. But through this attempt we hope to highlight both areas of agreement and the numerous points of uncertainty, doubt, controversy and consternation that fuel the great need for future missions in order to really learn the history of Venus.

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# IS THERE A GENETIC ASSOCIATION BETWEEN RIBBON TESSERA TERRAIN AND SHIELD TERRAIN, VENUS? V. L. Hansen<sup>1</sup>, <sup>1</sup>Department of Geological Sciences, 1114 Kirby Drive, University of Minnesota Duluth, Duluth, MN 55812 (vhansen@d.umn.edu).

**Introduction:** Venus host two distinctive terrains, one tectonic, the other volcanic. These two terrain types, ribbon tessera terrain and shield terrain are both extensively preserved across the surface of Venus, and they might also show a spatial correlation, which may, in turn reflect a genetic relationship.

**Geology:** Ribbon tessera terrain (rtt) represents the oldest locally exposed unit across Venus' surface. Unit rtt—variably marked by multiple wavelength contractional (folds), extensional (ribbons), and S-C-like shear structures—characterizes crustal plateaus (2-3 million km<sup>2</sup> quasi-circular highlands) and is preserved in large and small kipukas in the lowland (Hansen & Willis 1998; Ivanov & Head 1996). Detailed global geologic mapping indicates that rtt covers ~12% of the surface (Hansen et al. 2007; Hansen & Lopez 2008; unpublished mapping). Isopach calculations indicates that rtt lies at <1km deep across at least 48.5% of the surface.

Shield terrain, first recognized by Aubele (1996), comprises a volcanic terrain comprises of shield edifices (Guest et al. 1992) and shield paint, a low viscosity flow material (Hansen 2005). Shield terrain, in contrasts with shield fields (Crumpler et al. 1997) occurs across huge regions (millions of square km), significantly greater than the <300 km diameter areas of shield fields. Shield terrain appears to represents *in situ* partial melting at depth and subsequent translation of the melt material to the surface across extensive regions (Hansen 2005). Detailed geologic mapping indicates that shields and associated flow material (shield paint) form time-transgressively relative to fracture formation and local contraction, as evidenced by the formation of inversion structures involving shield materials and existing fractures. The formation of shield terrain remains a mystery.

Geologic mapping of several VMap areas reveals that shield terrain occurs in spatial correlation with rtt within crustal plateaus, as well as with regions that host large to small kipukas of rtt. Examples include (but are not limited to): Meskhert (V-3), Shimti Tessera (V-11), Vellamo Planitia (V-12), Nemesis Tesserae (V-13), Beta Regio (V-17), Niobe (V-23), Greenway (V-24), Agnesi (V-45), Aino Planitia (V-46), Helen Planitia (V-52) (Aubele 1996; Basilevsky 2008; Head and Ivanov 2005, 2008; Hansen 2008; Hansen and Tharalson submitted; Lang and Hansen 2008; Lopez and Hansen 2008; Stofan and Guest 2003; Stofan et al. 2003). There are also a few VMap quadrangles that are notable lacking in both ribbon tessera

terrain and shield terrain, such as Artemis (V-48), and Manuela Tholus (V-49), Barrymore (V-59) (Bannister & Hansen in press; Johnson et al. 1999).

**Implications:** The results of global mapping—both at the most detailed scale, as well as at the VMap scale by numerous individuals—are consistent with, and perhaps suggestive of, a genetic relationship between ribbon tessera terrain and shield terrain. Detailed mapping indicates that such a suggestion is worth consideration.

Ribbon tessera terrain may represent the surface 'scum' of huge lava ponds that formed on the surface of Venus in the ancient past (Hansen 2006). Within the context of the lava pond hypothesis, partial melting of the mantle results in the formation of the lava to supply individual lava ponds. Lava pond formation could result from the impact of individual large bolides with an ancient thin lithosphere (Hansen 2006). We explore possible scenarios of partial melting and differential crystallization that might result in a crustal-petrologic-geochemical environment that, could, in turn spawn shield terrain formation, following lava pond solidification. Shield terrain formation could evolve significantly after lava pond solidification, depending, at least in part, on later environmental conditions. The hypotheses to be presented might be tested through geochemical and or petrologic modeling.

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**GEOLOGICAL EVIDENCE FOR PETROGENETIC DIVERSITY ON VENUS: IMPLICATIONS FOR FUTURE EXPLORATION STRATEGIES.** James W. Head<sup>1</sup>, Mikhail A. Ivanov<sup>1,2</sup> and Alexander T. Basilevsky<sup>1,2</sup>, <sup>1</sup>Dept. of Geological Sci., Brown University, Providence, RI 02912 USA, (james\_head@brown.edu), <sup>2</sup>Vernadsky Institute of Geochemistry and Analytical Chemistry, RAS, Moscow 119991, Russia.

**Introduction:** A long-standing, fundamental question in planetary geoscience is: "How similar are the geological histories of Earth and Venus, and when and how did their evolution diverge?" Did Venus once have oceans and a more Earth-like climate, as suggested by Pioneer-Venus data [1]? If so, when, how, and why did it transition to current conditions, and are traces of this early period, and the transition, manifested in the currently exposed geological record? What is the evidence as seen in the surface products of mantle partial melts (the petrogenetic record)? Does Venus, like the Earth, have both mafic secondary crust (derived from mantle partial melts) and felsic tertiary crust (derived from reworking of secondary crust and potentially involving water) [2]. In this analysis we review evidence for the presence of mafic and felsic crust in the currently observed geological record of Venus in order to set a framework for addressing these questions.

Magellan radar image data revealed that the surface of Venus was composed primarily of plains units containing geomorphic features consistent with a volcanic origin [3]. Indeed, over 80% of the surface appears to have been resurfaced by effusive volcanic activity [4], primarily interpreted to be basaltic (mafic) in nature, an observation consistent with the geochemical results from the Venera/Vega landers [5]. A small number of features initially observed in the Magellan data (pancake domes [3,6-7], festoons [8]) differed from the widespread effusive, apparently low-viscosity lavas interpreted to be of basaltic origin, and were interpreted to be either of a more felsic nature [6-8], or to be basaltic magmas that attained higher viscosity through increased bubble content [6]. Subsequent to these initial global descriptions, numerous studies began placing geologic features in the context of local, regional and global stratigraphic relationships [e.g., 9]. The highly deformed tesserae were seen to be the earliest stratigraphic unit and were thought to represent either deformed volcanic plateaus or more ancient tectonically thickened crust that could be either mafic or felsic in nature [10]. Following tessera formation, a sequence of volcanic units with differing characteristics were observed, all apparently forming in the last 20% of the history of Venus [11]. Among the fundamental unresolved questions concerning the history of Venus are: 1) What is the petrogenetic diversity displayed by the array of volcanic features? 2) Is there evidence for significant compositional variation, perhaps ranging from ultra-mafic to felsic? 3) What are the geological envi-

ronments in which candidate felsic materials occur? 4) How do these environments relate to the emerging picture of the geological history of Venus? 5) What insight might these observations provide for the first 80% of the history of Venus and whether water might have played a significant role in the evolution of Venus? We first describe the features that suggest petrogenetic diversity, we then examine them in the context of the stratigraphic record, and we conclude with a series of outstanding questions and how these might influence future exploration strategy.

**Range of Geomorphic Features:**

**Tessera terrain** is high-standing, highly deformed terrain lying at the base of the stratigraphic column [12]; on the basis of its thickened crust and continent-like geomorphology (high-standing continent-like plateaus surrounded by marginal deformation belts) some have interpreted tessera to consist, at least in part, of ancient rocks, perhaps more felsic in nature [13]. Others interpret tessera terrain to be of basaltic origin, perhaps related to collapsed plumes [14] or tectonic crustal thickening processes of basaltic material [15]. Recent analysis of near-infrared thermal radiation data are interpreted to mean that the tessera may be more felsic in composition [16-18]. Thus, tessera terrain represents a prime candidate for further exploration for determining the petrogenetic history of Venus.

**Pancake domes** (now called farrum, singular farra) are clearly distinguished from mafic flows by their steep sides, generally circular shapes and similarities to viscous felsic domes on Earth [6-7]. Although among the most impressive candidates for higher-viscosity felsic volcanism on Venus, their felsic nature could not be distinguished, on the basis of morphology, from enhanced viscosity due to peculiarities of the Venus volcanic environment [6].

**Festoons**, located both in the plains and in the tessera [8,19-20], represent a class of features that also show similarities to felsic extrusive flows on Earth (steep-sided, very rough, lobate flows). Morphometric analyses suggest a viscosity consistent with andesitic-dacitic-rhyolitic flows on Earth [8].

**Geological and Chronological Settings:** Geological mapping at all scales has provided the opportunity to assess the stratigraphic positions and associations of these features and deposits, thus providing clues to their petrogenesis. **Tessera Terrain** is the best candidate for sampling ancient crust on Venus, crust that could represent the geological record of the first 80% of the history



of Venus [9]. Fragments of earlier crust could have been incorporated during the events that created the highly deformed tessera, could have further survived the most recent phase of geological activity as high-standing crust, and could provide exposed samples (ranging from felsic crust to reworked zircons) from an earlier period. Most promising in detecting and mapping out such areas are techniques that might map the location of felsic materials in the tessera [16-18].

**Pancake domes** are not randomly distributed in space and time; the vast majority appear to be correlated with an early mafic volcanic unit (shield plains) that represents significant globally distributed basaltic volcanism from tens of thousands of small source vents [21-22]. This association has been interpreted to mean that the pancake domes formed from associated distributed melting and remobilization of basaltic crust to produce more felsic compositions [11,21]. A second association is with the near-summit areas of later individual mafic shield volcanoes, interpreted to mean that pancake domes can also form more felsic compositions during the evolution of large magma reservoirs [23].

**Festoons** are also not randomly distributed across the surface, occurring both in the plains and in the tessera. One of the most prominent occurrences of these features is in Ovda Region tessera, where a 250 x 300 km feature estimated to be ~5500 km<sup>3</sup>, appears to have formed during a very short period of time at the summit of Ovda at ~4.4 km above MPR [19-20]. On the basis of the morphology, stratigraphic relationships, and tectonic setting (interpreted to be at the summit of terrain representing significant downwelling and crustal thickening), this unit has been interpreted as melting of thickened basaltic crust and generation of high-viscosity felsic magmas [19,24]. These correlations and interpretations provide some of the best evidence for the largest occurrences of candidate felsic crust on Venus.

**Summary and Implications for Exploration Strategies:** Several lines of evidence suggest that felsic crust is likely to exist on Venus among the following candidates: 1) felsic tessera components (analogous to continental crust), 2) viscous domes commonly associated with an early phase of distributed melting of basaltic crust (shield plains), 3) magmatic evolution in shield volcano reservoirs, and 4) festoon structures, the most prominent of which lies atop the highest tessera and may represent basal melting of thickened crust. Needed are: 1) more detailed analyses of tessera terrain to explore variations in structure [12], tectonic setting [10], thermal-IR characteristics [16-18], and interpretations [10,13-14,25-26]; 2) further analysis of the setting and associations of candidate pancake domes and festoons

[e.g., 27] in order to identify the most meaningful and accessible candidates for further exploration and investigation, and 3) identification of measurement objectives and exploration strategies to address these important questions [28-30]. Future exploration scenarios [31-32] should involve landers on tessera and pancake-domes/festoons, balloons that can obtain high resolution remote sensing data and touch-down chemical analyses, and orbiters that can help distinguish different units and surface mineralogy; these missions will pave the way for sample return. One of the most fundamental goals of the ongoing [33] and future exploration of Venus should be establishing the link between the currently observed geologic record and its petrogenetic diversity, and the nature of the first 80% of the geological, geodynamical and climate history of Venus [9,34-37].

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**Facing the heat - Obtaining near infrared real emissivity spectra at Venus surface temperatures.** J. Helbert<sup>1</sup>, A. Maturilli<sup>1</sup> and N. Müller<sup>1</sup>, <sup>1</sup>Institute for Planetary Research, DLR, Rutherfordstrasse 2, 12489 Germany - joern.helbert@dlr.de

**Introduction:** The Institute for Planetary Research has an expertise in spectroscopy of minerals, rocks, meteorites, and organic matter, build up in more than two decades. The available equipment allows spectroscopy from the visible to TIR range using transmittance and emission spectroscopy. The institute has an outstanding heritage in designing and building infrared remote-sensing instruments for planetary missions.

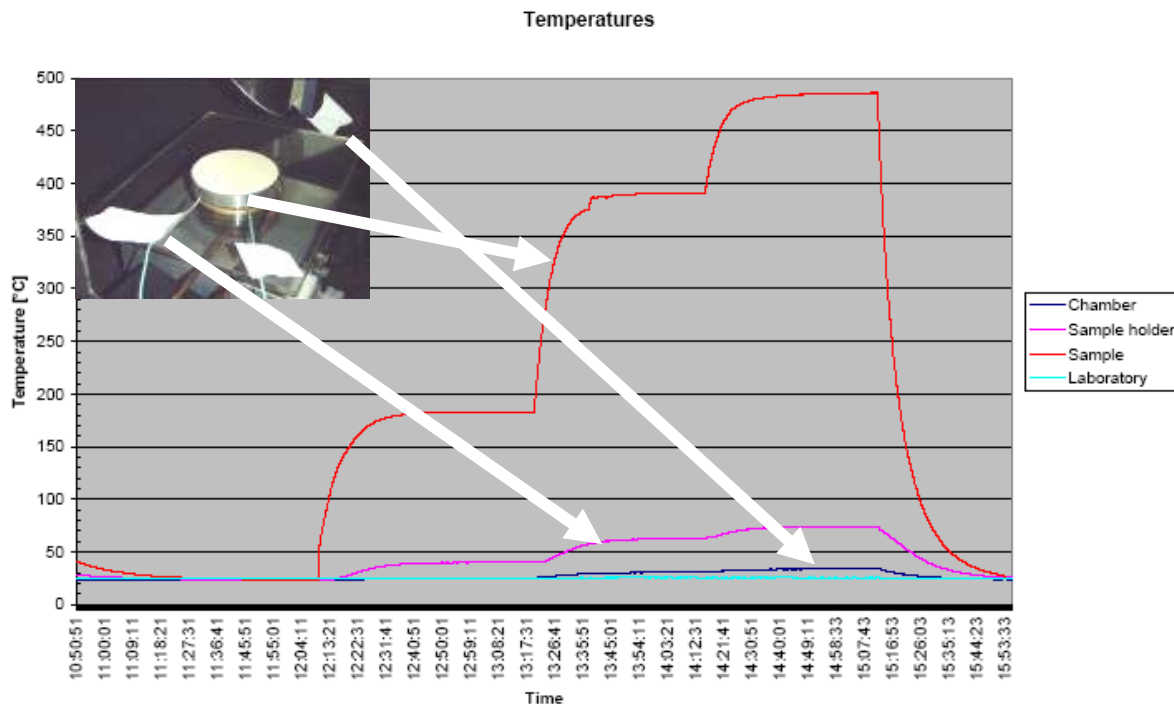
The heart of the spectroscopic facilities is the Planetary Emissivity Laboratory (PEL) which has been completely refurbished in the last two years. We will report here on the next development step of the PEL, which is the addition of a planetary simulation chamber. This chamber will allow to measure samples at temperatures up to 500°C and under vacuum. After this upgrade the PEL will be the first lab that can routinely measure the emissivity of fine grained samples from 1 to 50  $\mu\text{m}$  over an extremely wide range of temperatures.

**Planetary Emissivity Laboratory:** An emissivity spectrometer laboratory has been operating in various configurations at DLR for the last 10 years [1]. The laboratory experimental facilities consist of the main emissivity spectrometer laboratory, a supporting spectrometer laboratory for reflectance measurements, sample preparation facilities, and an extensive collection of rocks and minerals. The Planetary Emissivity Laboratory (PEL) in its current configuration was initiated by the installation of a new Bruker VERTEX 80V

Fourier Transform Infra-Red (FTIR) spectrometer in 2006. This spectrometer has a very high spectral resolution (better than 0.2  $\text{cm}^{-1}$ ) and a resolving power of better than 300,000:1, and it can be operated under vacuum conditions to remove atmospheric features from the spectra. To cover the entire spectral range from 1 to 50  $\mu\text{m}$ , two detectors, a liquid-nitrogen-cooled microthermocouple (MTC) (1-16  $\mu\text{m}$ ) and a room temperature deuterated triglycine sulfate (DTGS) detector (15-50  $\mu\text{m}$ ), two beamsplitters (KBr and multilayer), and two entrance windows (KBr and CsI) are used to measure the same target.

**High temperature emission spectroscopy:** The whole setup is very versatile and can provide measurements for a wide range of planetary application. However one goal that was always in mind during the planning and building up was obtaining emissivity spectra at a temperature range that would include Venus and Mercury dayside temperatures and with a wavelength coverage that would include the whole IR channel of VIRTIS on Venus Express. [2]

For the work we will presented here, a test setup was used building on the existing facility in the PEL. The main challenge to obtaining emissivity measurements at elevated temperatures is heating the sample without heating up the sample environment. The PEL will use a new and unique approach for heating the samples. Instead of a placing the sample cup on a heater and heating the sample cup by thermal conduc-



**Figure 1** Temperature profiles obtained during first test of the induction heating system

tion, the samples are placed in a stainless steel cup that is heated by an induction system. In the laboratory setup, a Linn Hightherm HTG-1500 induction heating system is used with a cooper pancake coil. Inside the coil water is circulated. The steel cup is placed on a glass ceramic plate, which in turn is placed on the coil. The system is placed inside the emissivity chamber and the chamber is sealed with a foam cover. To evaluate the thermal environment, three type K thermoelements with glass silk insulation are placed inside the chamber, one underneath the cup to provide its temperature, one placed approximately 2 cm away from the edge of the cup fixed to the glass plate with tape, and the third suspended inside the chamber about 10 cm away from the sample and the chamber walls. Finally, as a reference, a fourth thermoelement is placed outside the chamber to monitor the laboratory temperature. For the final setup the thermoelements will be replaced by a non-isolated type that will be inserted in the cups and fixed with ceramic glue that is temperature stable up to at least 800°C.

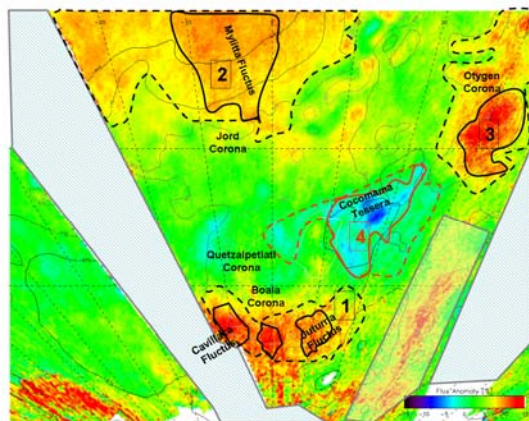
Figure 1 shows the temperature profiles recorded during one measurement series with an OMEGA TC-8 data logger. As can be clearly seen, the approach using an induction system actually does allow heating a sample to high temperature without heating the environment. This is an important point for emission spectroscopy, where the main concern is to minimize the thermal radiation from the environment. While the steel cup containing the sample reaches a temperature of up to 480°C, the sensor on the glass plate only 2 cm away from the sample cup never records more than 70°C. The increase in chamber temperature is less than 5°C, making the contribution of thermal radiation from the environment to the measured signal almost negligible.

The setup uses an internal calibration source that consist of a coated steel plate. A thermoelement is imbedded in the steel plate allowing to assess the temperature. Due to its base material the calibration source can be heated by the induction system similarly to the steel sample cups. The coating of the calibration source is characterized using our standard setup. This allows to link the high temperature measurements directly with the measurements obtained using the standard setup.

**Application to Venus:** The laboratory work we are currently starting is in direct support of our work on VIRTIS [3,4,5]. Using the atmospheric windows in the near infrared we have mapped brightness variations on the surface of Venus which we associate with emissivity variations. These variation which show correlations with geological units are indicative of variations in the surface composition of Venus. An example from [3] is shown in Figure 2. For the Lada Terra region of Venus

gion of Venus the analysis indicates a higher than average emissivity for fresh lava flows and a lower than average emissivity for the old tesserae terrain.

In order to draw any conclusions on actual mineralogy it is necessary to obtain emissivity values for appropriate analog materials at realistic temperatures in the same wavelength range. So far there are no such measurements available. The applicability of low temperature reflectance spectra converted to emissivity using Kirchoff's law leaves a large uncertainty.[6]



**Figure 2 Brightness anomalies observed in the Lada Terra region of Venus with VIRTIS on Venus Express [3]**

We have just started to work towards measurements in this range. For a first set of test measurements we will focus on anorthosite and basalts as typical end-members for a very simplified surface mineralogy.

**Conclusions:** The PEL will allow to obtain a unique new set of measurements that will greatly support the analysis of data retrieved using the near infrared windows of Venus. It will also strongly support the design of camera and spectrometer system for future Venus missions [7].

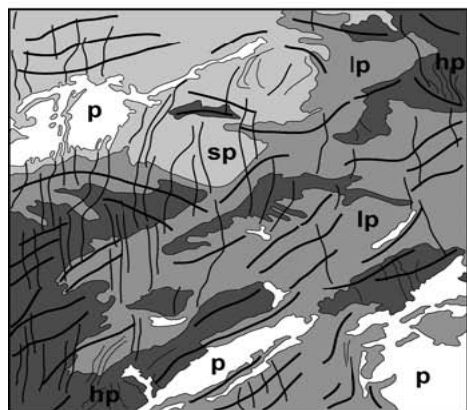
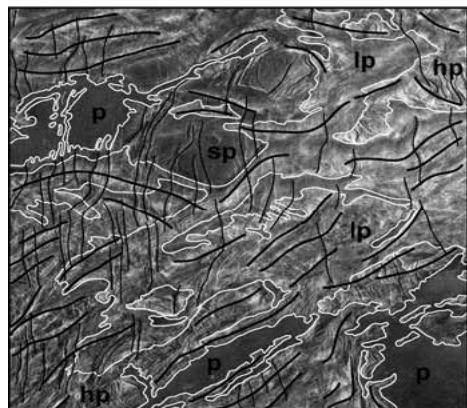
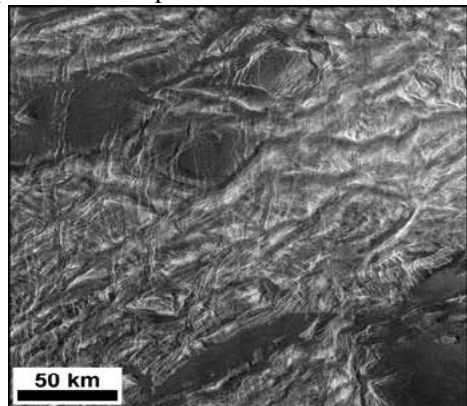
We will present here the very first result of this exciting new work.

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**An Analysis of the Nature of Tessera Materials on Venus,** M.A. Ivanov<sup>1,2</sup>, and J.W. Head<sup>2</sup>; <sup>1</sup>Vernadsky Institute, RAS, Moscow, Russia, <sup>2</sup>Brown Univ., Providence RI, USA.

**Introduction:** One of the major and outstanding problem in Venus geology is: Does Venus possess a non-basaltic crustal component which may be an analog to the continental crust of Earth [e.g. 1]? Detailed photogeologic analysis of plains units that make up the majority of the surface of Venus strongly suggests that the plains were formed by eruptions of low-viscosity lavas [2-4]. Such a morphology is interpreted to be an indicator of the basaltic composition of the plains and correlates well with the results



of direct chemical measurements on the surface made at seven points [5-7]. These two independent sources of data, along with the absence of liquid water and, hence erosion

[8,9] suggest (1) that basaltic volcanism is the chief process of formation of crust on Venus [2] and (2) that the morphology of the plains indicates that their emplacement involved extrusive lava flows. The only features whose morphology suggests more evolved material compositions are steep-sided domes and festoons [2,10,11].

In contrast to the plains, tessera terrain is so heavily modified by tectonic deformation that the primary morphologic characteristics of its precursor materials are not readily seen. Additionally, tessera often occurs in large high-standing regions that are clearly older (embayed) than surrounding plains. In these characteristics, tessera to some degree resemble terrestrial continents (old, high-standing, tectonized massifs), the bulk of which are made of non-basaltic materials [e.g. 12]. Thus, if a non-basaltic component of the crust indeed exists on Venus, tessera appears to be one of the best candidates. No spacecraft has landed on the surface of tessera and the composition of its surficial material is unknown [13-15]. Without these types of data, detailed morphologic analysis of relicts of the tessera precursor may provide important information to assess the possible nature of the tessera material.

**Morphology of the tessera precursor terrain:** The main goal of our study was to analyze the morphologic characteristics of the oldest materials in tessera that predate the tessera-forming deformation. We randomly selected 56 points from the entire tessera population and analyzed the morphologic characteristics of the surface. Each point represents a region ~77 by 77 km from the F-MAP mosaics with the best available resolution, 75 m/px. All large tessera regions and a number of small tessera areas have been sampled. An example from Ovda Regio (Fig. 1) illustrates a typical set of intra-tessera units and structures, and their relationships. The structural pattern of tessera in this area consists of broad ridges and valleys (characteristic spacing is ~15-20 km) oriented preferentially in E-W and NE directions, and narrow (a few km wide) box-shaped graben oriented mostly in the N-S direction. These structures cut three morphologically distinctive units and are embayed by undeformed plains (p), which represent the youngest units emplaced after cessation of tessera-related tectonic activity. The units predating the tessera-forming structures are as follows: *Hummocky plains (hp)* have a rugged surface consisting of low hills/knobs that are deformed by numerous low scarps, ridges, and valleys. The dimensions of these features are about an order of magnitude smaller than those of the tessera-forming structures. In places, knobs within the hummocky plains have flat summits with plains-looking morphology. *Lineated plains (lp)* have a smoother surface that is cut by sets of parallel narrow lineaments with typical width and spacing <1 km, down to the resolution limit. Material of lineated plains appears to embay some of structures in hummocky plains and, thus is interpreted to be

younger. *Smooth plains (ps)* appear to be morphologically smooth and relatively featureless at Magellan resolution. The plains are deformed by broad tessera ridges and embay structures of lineated and hummocky plains. These observations suggest that the original terrain in Ovda tessera represented a complex of plains units morphologically similar to those outside of the tessera region. The plains were emplaced and deformed during several episodes of volcanic and small-scale tectonic activity, and later deformed into the tessera pattern by much more intense tectonic episodes.

Similar types of plains occur as pre-tessera material in all other tessera regions that we studied. The most frequent types of these plains are smooth and lineated plains. They occur, respectively, within 52 and 45 studied tesserae. Hummocky plains occur in 26 different mapped areas. All three types of plains, hummocky, lineated, and smooth, occur within 18 tessera areas (32%), any two types of the plains occur within 31 areas (55%), and within 7 areas (13%) only one type of plains represents the pre-tessera precursor material.

**Discussion:** In all analyzed tessera fragments, relicts of various plains units are recognizable. Several lines of evidence suggest that these units represent tessera precursor materials. First, and most important, the plains are deformed by the rough-scale structures (broad ridges, graben, etc.) that make up the characteristic structural pattern of tessera. Second, the fine-scale features on the surface of the plains are about order of magnitude smaller than the typical structures of tessera. This suggests that the tectonic deformation of the plains took place under conditions different from those that were in effect when the rough tessera surface formed. Third, in many places there is evidence that pre-tessera plains embayed each other. The rough-scale tessera structures do not control the boundaries of the plains units.

The plains morphology of the pre-tessera materials strongly suggests that initially these were lava plains. If the common interpretation of lava plains on Venus as basaltic plains can be extrapolated back to the time of emplacement of the pre-tessera materials, then one can conclude that tessera terrain is largely made from deformed basaltic lavas. Such a conclusion is supported by the absence, in the pre-tessera plains, of steep-sided lava fronts that indicate relatively high viscosity of lava [10] and possibly more evolved composition of erupted materials.

The largest tesserae form the summits of the regional highlands [16-18]. It is conceivable that tessera may represent a relatively thin skin of tectonized basaltic plains that covers a more silicic core of highlands [19,20]. The post-tessera volcanic activity inside the highlands can be used to assess this possibility. Post-tessera volcanic plains (p) are seen within each large tessera region. The individual occurrences of the plains (10-100s of km across) form isolated patches probably related to multiple sources of lavas. The depth of generation of the plains is unknown. The sources could be either within the tessera highlands crust, or beneath, in the mantle. In the first case, the material of the post-tessera plains is merely the remelted and erupted material of the highlands. The morphology of these plains suggests that they have a basaltic (or even less silicic) composition.

If the sources are in the mantle beneath the highlands crust, the material of the plains would represent melts originating from the mantle and would not be characteristic of the material of the highland crust. If this was the case and if the hypothesis of a granite-like composition for the main portion of the interior of tessera plateaus is valid, one might expect some kind of interaction between rising mantle melts and the crustal material of the plateaus.

On Earth, intrusion of the hot mantle melt into continental crust, which has a lower melting point, leads to local heating and remobilization of crustal material [21-24]. Sometimes, for instance in regions of continental rifting, this results in silicic volcanism with its characteristic morphology: the formation of rhyolitic steep-sided domes and scalloped flows [25,26], explosive calderas [27-29], and cinder cones [30,31]. If we assume that in the tessera highlands a granite-like material is hidden beneath the basaltic tessera crust, then, by analogy with the Earth, we might expect to see some morphologically recognizable manifestations of such material in the areas of intratessera volcanism (for example, the flows of viscous lava with a distinct frontal scarp [2,11] or steep-sided domes [10]). The morphology of these features may indicate a more silicic, as compared to basalt, composition. Only one steep-sided scalloped flow [32] and one steep-sided dome

[10] are observed within the entire tessera terrain on Venus. Large structures similar to the Earth's explosive calderas are absent within the tessera, and there are no volcanic edifices with a large crater-to-base diameter ratio, which is a typical feature of explosive volcanic edifices [30,33]. Thus, one can conclude that manifestations of non-basaltic (probably silicic) volcanism within tesserae are not abundant. This means that the hypothesis for the non-basaltic, granite-like composition of the major portion of the bulk of the tessera highlands [1] has little support from these observations. Currently, the model of tessera highland interiors in which the bulk of the highlands is composed of "basalt", with a possibly minor "granite" component, appears more likely.

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**CORE FORMATION ON THE TERRESTRIAL PLANETS: COMPARATIVE PLANETOLOGY OF THE EARTH, MOON, MARS, VESTA, AND VENUS.** J.H. Jones, KR, NASA/JSC, Houston, TX 77058 (john.h.jones@nasa.gov)

**The Boundary Conditions:** Basalts from the Earth, the Moon, Mars, and Vesta are strongly depleted in elements that prefer to reside in the metallic state (siderophile elements). Therefore, it is believed that all these bodies have metallic cores. We do not yet have siderophile element analyses of venusian basalts, but we assume that Venus, too, as a terrestrial planet, has a metallic core. For the Earth, Moon, and Mars, the moments-of-inertia of these bodies are consistent with metallic cores of various sizes. Because Venus rotates so slowly, it may be difficult to determine the moment-of-inertia of Venus in order to confirm this assumption.

**Experimental Constraints:** The fundamental experimental constraint on core formation at low pressure comes from the work of Stolper [1] on eucrites. He found that, in order to saturate eucritic liquids with metallic iron, it was necessary to achieve oxygen fugacities of  $\sim IW-1$  (a log unit below the iron-wüstite oxygen buffer). This makes good physical-chemical sense. Eucrites are not wüstite-saturated, and therefore require redox conditions significantly below the IW buffer before they can come into equilibrium with metallic iron.

A second fundamental experimental constraint comes from Walker et al. [2], who noted that lunar mare basalt compositions that were experimented on in pure iron capsules at 1-bar to 30-kbar did not gain or lose FeO. This implies that lunar basalts are nearly saturated in metallic iron at about IW-1. This is corroborated by the frequent presence of metallic iron in the mesostases of lunar mare basalts [3].

Finally, Jurewicz et al. [4] found that partial melts of chondrites held at IW-1 [one-bar gas-mixing] contained about 18 wt.% FeO. Therefore, the origin of basalts with 18-20 wt.% FeO seems well constrained at low pressure.

**Generalizations:** Both lunar basalts and eucrites have the general property that they have FeO contents of  $\sim 18-20$  wt.%. Combining the work of [1,2,4], it seems clear that, at low pressure ( $< 50$  kbar), planets such as the Moon and Vesta conspire to produce basalts with 18-20 wt.% FeO if their source regions were in equilibrium or near-equilibrium with iron metal at IW-1.

A third planet that produces basalts with 18-20 wt.% FeO, and which is known to have a metallic core,

is Mars. We know the FeO content of martian basalts by analyses of martian meteorites, and we know that Mars has a metallic core from its moment of inertia. By inference therefore, it is likely that martian basalts also come from source regions that once had an oxygen fugacity of  $\sim IW-1$ . Oxygen fugacity measurements on primitive martian meteorites confirm this inference. Spinel-ilmenite assemblages in primitive martian meteorites yield oxygen fugacities in the vicinity of IW [5] and these oxygen fugacities should be upper limits to that of the source regions of these basalts [6].

Therefore, the Moon, Mars, and Vesta are consistent with low pressure ( $< 30$  kbar) experiments that constrain the initial conditions of core formation on these bodies to have been at  $\sim IW-1$ , with the subsequent production of basalts that have 18-20 wt.% FeO.

**The Earth and Venus:** The exceptions to this self-consistent picture are the Earth and Venus. Basalts on these planets have FeO contents of 8-10 wt.% [7] — roughly half that of the “self-consistent” group.

The most assured difference between the Earth and Venus on the one hand and the “self-consistent” terrestrial planets on the other is size and mass. Mars is the largest “self-consistent” planet and it may generate core-mantle-boundary pressures in the vicinity of 250 kbar [8]. Alternatively, the Earth and Venus may have core-mantle pressures of  $\sim 1400$  kbar [9].

This observation suggests that the Earth and Venus have FeO contents that are dominated by high-pressure, rather than low-pressure, equilibria. Various authors have speculated on the cause of the FeO content of the Earth’s mantle, but common themes have been to ascribe the Earth’s FeO abundance either to pressure [e.g., 10] or to heterogeneous accretion [e.g., 11].

Perhaps the strongest argument against heterogeneous accretion is that most terrestrial bodies, i.e., the Moon, Mars and Vesta, do not manifest any indication of such. For example, the Moon, which appears to have formed in proximity to the Earth, has the FeO content and oxygen fugacity that would be predicted from eucrite experiments [1]. Therefore, there is at least circumstantial evidence that the FeO contents of the Earth and Venus are determined by high pressure equilibria [10].



**Mechanisms?:** The simplest mechanism for reducing the FeO content of an Earth-sized body is for FeO to become soluble in liquid iron metal [10]. In other words, the core could become a sink for FeO, reducing the FeO content of the mantle. Alternative mechanisms involving metal-perovskite-magnesiowüstite equilibria seem less likely.

**Implications:** One immediate contrast is the difference in FeO content between lunar and terrestrial basalts. Both bodies presumably formed near 1 AU and formed from the same feeding zone of planetesimals. If, for example, the Moon formed from the Earth by a giant impact, then this event must either have occurred before high-pressure equilibria had the opportunity to deplete the Earth's mantle in FeO or the bulk silicate Moon is dominated by material from the impactor.

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## SOVIET LANDER AND MAGELLAN DATA POINT TOWARD EARTHLIKE VENUS GEOCHEMISTRY AND VOLCANOLOGY, WITH SOME DIFFERENCES, AND MANY QUESTIONS. J.S. Kargel<sup>1</sup>

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**Introduction:** Seven successful Soviet Venus landers reported compositional information on Venus surface rocks [1-3], and Magellan SAR discovered a wide range of familiar Earthlike volcanic landforms amidst a partially dissimilar tectonic landscape. The landers produced compositional data and surface imagery consistent with orbital views indicating or suggesting volcanic landing sites associated with a variety of tectonic environments, including what appears to be both rift and hotspot styles of volcanism [4]. The precision of the lander chemical analyses was poor [5]; only three landers reported major element compositions for most major oxides assessed by X-ray fluorescence, but not Na<sub>2</sub>O at all. Some landers also reported K, U, and Th determined by gamma ray emissions. Venera 8, the first successful lander, reported such high amounts of K<sub>2</sub>O that it was definitively concluded that Venus has an extremely differentiated crust, with K attaining a couple hundred times CI chondrite abundances. Granite was the preferred interpretation.

**Reassessments of Soviet geochemistry data:** Kargel et al. [4] provided a more complete assessment of the Soviet data in conjunction with RADAR imagery and concluded that alkaline volcanic rocks may be more common on Venus than on Earth, and the Venera 8 sample was possibly one of those (while not ruling out a granite interpretation). Treiman [5] produced the most complete assessment of the full impact of instrumental errors on the possible interpretations, preferring more conservative 2- $\sigma$  errors (95% confidence limits) as is standard in geochemistry. Analysts of the Venus data agree that they indicate a silicate body having a metallic Fe-rich core and FeO-rich mantle and that the crust is heterogeneous and includes parts that are highly differentiated relative to the mantle.

I reiterate and support what Treiman stated about the limitations of interpretations due to large measurement errors, but the figures below [from 4] use 75% error bars. Certain conclusions are probable at 75% limits of confidence [4]; fewer things can be concluded at 95% limits of confidence [5] (Table 1).

In fact some really profound things can be stated with 95% confidence (or greater); more things can be concluded with 75% confidence, which is not great confidence, but it is enough to start framing some hypothesis for future investigation by new Venus probes. Among the findings is that at 75% confidence, Venus

may have a far greater incidence of highly alkaline volcanism than on Earth, but overall, Venus seems Earthlike in composition [5] (Table 1).

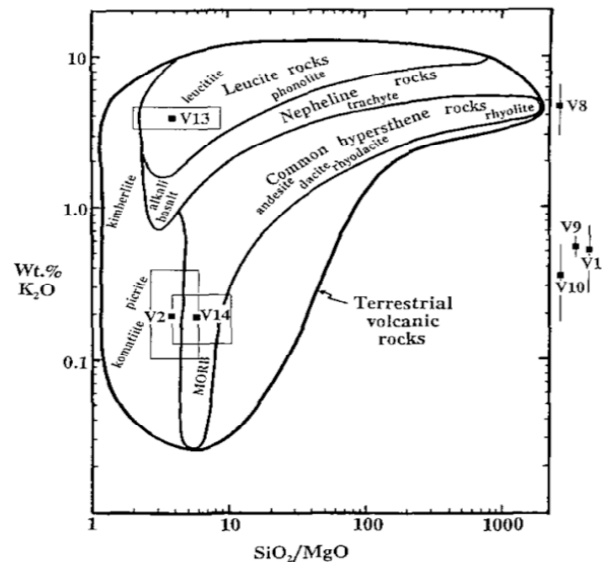


Fig. 1. This important set of chemical parameters shows how 75% confidence limits of Soviet lander data relate to terrestrial volcanic rocks. The compositional range is related to degree of partial melting, volatile abundances in the mantle source, and fractional crystallization. Venera 14 (V14) and VEGA 2 (V2) data are consistent with the composition of common Mid Ocean Ridge Basalts and basaltic tholeiite shield volcanic rocks on Earth, whereas the Venera 13 (V13) sample occupies a sparsely populated field of rare alkaline hotspot volcanic rocks, kimberlite pipes, and other volcanics fed from CO<sub>2</sub>-rich mantle. See Kargel et al. (1993) for details, but the bottom line is that, at 75% confidence, V13's sample is consistent with <1% partial melting of Earth-like CO<sub>2</sub>-rich mantle, whereas V2's and V14's rocks suggest 5-30% partial melting of dry mantle. All three rocks are consistent with little fractional crystallization. Treiman [6] points out that with 95% error envelopes, especially on magnesium, results could be very different.

**Geology of the landing sites from Magellan SAR:** Kargel [5] provided an integrated geological and geochemical perspective on the landing sites. Venera 14 (V14) and VEGA 2 (V2) reported Mid Ocean Ridge Basalt-like compositions; V2 landed on a vast effusive lava flow field associated with Sith Corona (Fig. 2),



Table 1. Key conclusions about Venus [4,5] from geochemistry of rocks [1-3]

Confidence:	75%	95%
It is a silicate world	Yes	Yes
It has a Fe-rich core:	Yes	Yes
It has grossly basaltic rocks	Yes	Yes
It has MORB-like rocks	Yes	Maybe
It has highly alkaline mafic rocks	Yes	Maybe
Alkaline mafic rocks are abundant	Maybe	Maybe
It has granitic rocks	Maybe	Maybe
It has Ca-Al-Ti fractionation	Yes	Maybe
Mantle role of CO <sub>2</sub> or H <sub>2</sub> O	Maybe	Maybe
Mantle role of garnet	Maybe	Maybe
It resembles Earth overall	Yes	Maybe
It resembles Mars overall	No	Maybe
It resembles eucrite parent body	No	Maybe
It resembles Earth's Moon	No	No
We have good geochem sampling	No	No

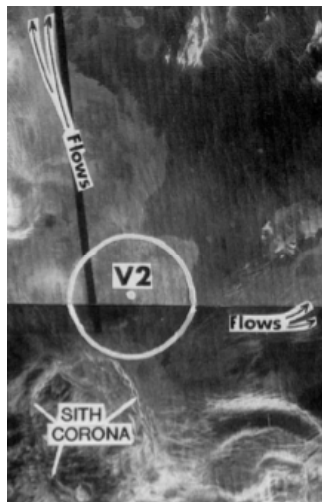


Figure 2. VEGA 2 site.

whereas V14 landed on effusive flow field emanating from a large shield volcano (Fig. 3). The ultrapotassic V13 site is along a volcanic rift (Fig. 4) and includes several near-by “pancake domes,” which could be products of intra-crustal differentiation. The other high-K rock (V8) is from a region near or with-in a field of small shields or cinder cones, which may have a nearest analog in terrestrial continental mid-plate hotspot volcanism. In all, a variety of volcanic/tectonic terrain types were analyzed, but many terrain types on Venus remain unsampled [4,5]. Future exploration could resolve the degree to which highly silica undersaturated or other unusual volcanic rock types (e.g., Figs. 1 and 5) really are common and why this might be.

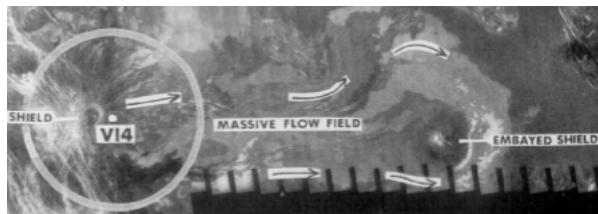


Figure 3. Venera 14 site on a large shield volcano.

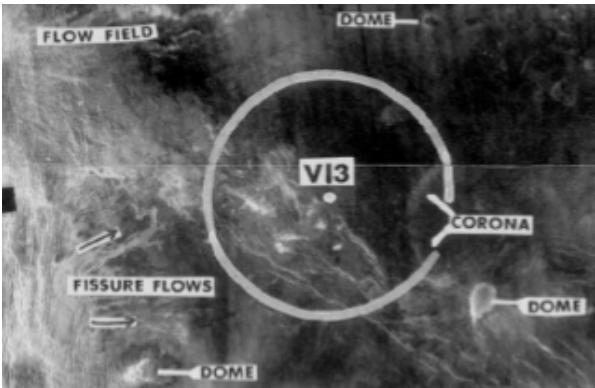


Figure 4. Venera 13 site along a volcanic rift.

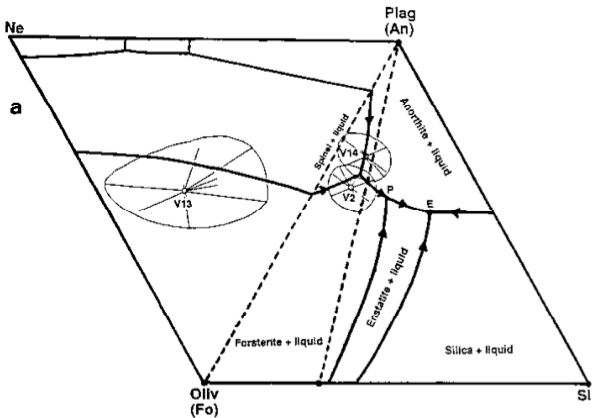


Figure 5. CIPW norms of Venera 13 and 14 and VEGA 2 rocks, as described more fully by Kargel et al. [4]. Within 75% error limits, the samples plot as olivine normative, with Venera 14 and VEGA 2 being what would be considered basaltic tholeiites or olivine tholeiite basalts, and Venera 13 being a highly silica-undersaturated mafic rock. If 95% uncertainty envelopes on element abundances and unknown amounts of sodium are considered, all bets are off, as Treiman [5] has calculated and explained in detail.

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## MELTING VENUS: POTENTIAL GEOCHEMICAL DIAGNOSTICS OF MANTLE SOURCE DEPTH

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### Introduction

Volcanism on Venus has produced a rich array of volcanic landforms [1], which in turn suggests a broad range of magma production and differentiation environments. In the next decade, it is possible that one or more landers associated with New Frontiers or Flagship class missions to Venus will provide new geochemical observations of the Venus surface. The goal of this work is to make an initial assessment of how such geochemical observations may help to constrain magma production depths on Venus.

### Magmatic Environments on Venus

Volcanism on Venus occurs in a variety of geologic environments that suggest varying mantle source depths for magma production. Volcanic rises such as Beta Regio and Atla Regio are likely formed over hot, upwelling mantle plumes [2, 3], with magma produced as deep as 170 km (5 GPa) [4]. Coronae are probably formed by diapiric upwellings [5], possibly under regions of lithosphere that are thinner than for volcanic rises [6] and thus melting occurs at lower pressures. Large flow fields are commonly associated with rifts and fracture belts [7], for which the observed fracturing and extension suggests a relatively thin lithosphere and low pressure magma generation.

In preparation for proposed future spacecraft missions to Venus, we therefore consider the extent to which likely geochemical instrumentation on short-lived landers may be able to place constraints on mantle source depth. We do not consider the possible effects of near-surface fractionation, which are discussed in another abstract [8]. Such fractionation likely has occurred in some places. For example, shield fields on Venus may contain 100 or more small shields in a single large volcanic field [9, 10]. Such fields are likely fed by a single large magma chamber, which would provide an environment suitable for shallow magmatic fractionation. The proposed environment is similar to the Marius Hills on the Moon, for which gravity observations provide clear evidence for a regionally extensive magma chamber [11].

### The Mantle Source Composition

An essential aspect of any magma production calculation is the assumed composition of the mantle source region. We focus specifically on basaltic vol-

canism, which appears to dominate the surface of Venus. Issues related to production of non-basaltic magmas on Venus are considered in [12]. Numerical accretion simulations suggest that there was probably considerable radial mixing within the solar nebula [13]. Thus, to first order, it is reasonable to assume that the mantles of Venus and Earth had similar primordial compositions. For this reason, we will assume for the purpose of this work that the Venus mantle is similar to the terrestrial KLB-1 mantle peridotite [14], which is representative of basaltic source region compositions on Earth [15]. The available geochemical measurements from the surface of Venus are basically consistent with this, but with large measurement uncertainties [16, 17]. We assume a dry mantle source region, which is consistent with the apparent absence of a low viscosity asthenosphere in the mantle [2].

We note, however, that the preservation of distinct oxygen isotopic reservoirs in many parts of the solar nebula [18] implies that radial mixing in the nebula was at best imperfect. As a result, there may well be subtle but important differences in mantle composition between Venus and Earth. Results for Mars derived from the chemistry of the martian meteorites may be instructive. In comparison to Earth, Mars appears to have a somewhat lower Mg number (the molar  $\text{Mg}/(\text{Mg}+\text{Fe})$  ratio) and to be enriched in alkalis [19, 20]. Together, the two effects lower the martian mantle solidus by about 35 K relative to terrestrial peridotites [21], which has a significant effect on the calculated magma production [22]. Based on these considerations, we may also consider other peridotite starting compositions to assess the sensitivity of our results to small changes in mantle source region composition.

### Geochemical Measurements

For the purpose of this work, we assume that a relatively basic suite of geochemical measurements will be possible on the next generation of Venus lander. These include measurements of major element composition by an X-Ray Fluorescence Spectrometer, of U, Th, and K by a Gamma-Ray Spectrometer, and of mineralogy by an X-Ray Diffraction Spectrometer. X-Ray Fluorescence and Gamma-Ray spectroscopy have both been performed at a variety of locations on Venus [23, 24]. Because U and Th are both refractory (and thus likely to have been initially present in chon-

ditric abundances) and highly incompatible (and thus concentrated in the melt phase), the Gamma-Ray Spectrometer might be thought of as a “partial melt fraction meter”, although interpretation of such measurements obviously depends on whether a given mantle parcel has passed through the melting zone on more than one occasion. Possible approaches for measuring important minor and trace elements such as Na, Ni, and Co are described in [17]. X-Ray diffraction might be done with an approach similar to the ChemMin instrument suite being developed for Mars Science Laboratory [25]. If it can be adapted for use at Venus ambient conditions (including the need for extended integration periods), it may provide at least semi-quantitative constraints on the rock mineralogy. Finally, some sort of drill system is needed to core beneath any surface weathering layer.

### Magma Composition Modeling

The observations cited above suggest that magma on Venus may form at a broad range of pressures, from about 0.2 GPa at the base of the crust to perhaps 5 GPa in mantle plumes. The available petrology literature [e.g., 26, 27] suggests that simply varying magma production depth for a fixed mantle source composition can imprint recognizable chemical fingerprints on the resulting basalts.

To further explore this, we are performing a series of melting calculations using the thermodynamically based MELTS and pMELTS programs [28, 29]. For our specified mantle source composition, we consider temperatures that result in melt fractions ranging from a few percent to as much as 20%. The upper end of the melt fraction range on Venus is not known, but presumably the highest melt fractions occur in shallow melting environments such as rift systems. For each combination of temperature and pressure, we calculate the liquid composition that is in equilibrium with the mantle source composition. Melting calculations up to 1 GPa are done with MELTS and calculations at 1-3 GPa are done with pMELTS. Although melting may occur at pressures greater than 3 GPa on Venus [4], we do not model this because of the limitations in the experimental thermodynamic database used in pMELTS [29].

Each magma composition is then transported to the surface without fractionating at intervening depths. It is crystallized at the ambient surface pressure and the normative mineralogy is calculated. We are assessing possible trends in basalt elemental composition and mineralogy as a function of melting depth and melt fraction. For example, does the source depth cause

changes in the Mg number or the alkali abundance? How do the relative abundances of plagioclase, clinopyroxene, orthopyroxene, and olivine vary with initial melting depth? Can the appearance or disappearance of accessory minerals be used as a melting depth indicator? Because of uncertainties in the mantle source composition and because we have not included near-surface fractionation, our results may not provide precise melting depth indicators. Moreover, in practice melting will typically occur over a range of depths, which will at least partially blur the patterns in real rocks. Our hope, however, is to identify trends which are sufficiently robust that they can at least serve as guides to the initial melting depth.

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**SURFICIAL DEPOSITS AND ACCESS TO MATERIALS WITH KNOWN GEOLOGICAL CONTEXT ON VENUS.** *M. A. Kreslavsky*<sup>1</sup>, <sup>1</sup>Earth and Planetary Sciences, University of California - Santa Cruz, 1156 High Str. Santa Cruz, CA, 95064, USA; mkreslav@ucsc.edu

**Introduction:** Landing on Venus and geochemical investigations of Venusian materials either in-situ or with returned samples are thought to be of the highest priority in future scientific robotic exploration of Venus. Harsh conditions at the surface strongly limit mobility and operations at the landing sites, as well as the total number of different samples that can be analyzed. This makes it especially important that the samples are taken from known and pre-planned geological situation; for example, it would be desirable to understand, how to reliably get unaltered igneous material, altered material from a known source, etc. This is not easy, because remote sensing of Venusian surface is principally limited due to thick layer of clouds. Here I summarize relevant current knowledge on Venusian surface layer and apply it to analysis of accessibility of materials with known geological context. I consider here typical terrains in the vast Venusian plains and do not consider the exotic materials at high elevations.

**Volcanic units seen in SAR images.** Information about geology and surface properties has been obtained mostly with microwave remote sensing techniques. Imaging with the synthetic-aperture radar (SAR) on the Venera-15,-16 Venus orbiters, then from the Earth with the Arecibo radar facility, and, finally, by the Magellan orbiter has revealed a spectacular surface dominated by extensive volcanic deposits and deformed by abundant tectonic features. The generally pristine appearance of the volcanic morphologies indicates a very low rate of exogenic resurfacing during the recent half-a-billion years long geologic history. This pristine morphology gives a good chance that the original volcanic material is preserved, but it would be wrong to assume that it is accessible immediately at the surface. The sharp lava flows outlines seen as pristine morphology in the SAR images (the best resolution is ~200 m) can be preserved even if the original flow surface is heavily reworked or covered by meters of secondary surficial deposits. A number of lines of evidence show that this is the case in many locations on the planet.

**Dust deposits:** There are about a thousand of impact craters on Venus. Impact process inevitably produces at least some fine dust, which was inevitably suspended in the dense atmosphere and could be redistributed and deposited regionally or globally. Such dust can contaminate the surface with altered materials from distal sources. Thin (a centimeter or thinner) dust does not have any unique signature in the microwave remote sensing data. Deposits of fine dust under the

Venusian conditions will sinter. It is probable that it will be difficult to distinguish between sintered dust and rinds of altered local material, if we try to do this with panoramic or microscopic images. In any geological situation at the landing site, least some digging and/or rock abrasion capability is needed to be sure that samples are local materials rather than altered dust deposits from unknown source.

**Surficial deposits at Venera landing sites:** The morphology of the surface seen in the panoramas taken by Venera landers is not consistent with unaltered lava flows. Two of four panoramas contain soil. Rocks seen in the panoramas were reported to be similar to indurated sediments [1,2] or degraded lava flows [3]. Some lander data also indicate low density and mechanical weakness of the surface material [e.g., 4, 5]. Surface at the landing sites perhaps contains altered and/or non-local material.

**Surficial deposits seen in the SAR images:** Magellan SAR images revealed a number of eolian features: different types of wind streaks, two large fields of dunes and a few occurrences of unresolved micro-dunes [e.g. 6, 7]. It is not known, if such features form due to eolian reworking of local material or there is regional or global transport. Additional analysis of available remote sensing data may give some additional information on this.

A significant part of the surface is covered by extended crater-related diffuse features, including parabolas [e.g., 8, 9]. Several independent lines of evidence suggest that these features are mantles of microwave-transparent material with flat upper surface. The most important of such observations are: observation of a linearly polarized component in the Arecibo dual-polarization radar imaging experiment [10], the absence of decameter-scale topographic asymmetry [11], and low decameter-scale roughness. These observations are consistent with commonly accepted interpretation of the parabolas as airfall deposits of loose material ejected by impact events and moved westward by atmospheric superrotation. Pristine parabolas can give easy access to material from known source. This material can be altered, but alteration conditions in this case are well understood.

**Indirect indication of surficial deposits from microwave remote sensing.** Observations of backscattering anisotropy in the Magellan radar altimeter experiment indicate ubiquitous asymmetry of surface topography at the scales of decameters [12, 11]. This asymmetry has been attributed to the presence of

decameter-scale eolian bedforms. In [13] similar ubiquity of meter-scale asymmetric features has been found from analysis of left- and right-looking Magellan SAR images. These observations clearly indicate that loose material reworked by wind is much more abundant than would be deduced from observations of eolian features with SAR mosaics. It is not known, if these eolian bedforms are active now or if they recorded wind action in the geological past. It is possible that all eolian activity occurred only during short periods of atmospheric disturbance caused by large meteoritic impacts. It is also unclear, if eolian activity is / was able to move material for long distances to produce global material mixing, or the bedforms reflect only local reworking of the material. However, it is clear that some surficial deposits are present almost everywhere.

Some crater-related parabolic features seen in the microwave emissivity maps [14] are invisible in the SAR mosaics; probably, such features represent thin deposits. Emissivity maps as well as Aresibo dual-polarization SAR maps [10] and Magellan backscattering anisotropy maps [11] show that the spatial extent of the smooth-surface mantle is significantly wider than the dark parabolas and halos seen in the SAR mosaics [15]. This again shows the presence of surficial deposits in places where they are unseen in the SAR mosaics.

Stratigraphically older surfaces usually display lower contrasts in radar cross-section than the young surfaces, which points to some processes of surface aging [16]. This is naturally explained by accumulation of the surficial materials, which replace the originally varying backscatter signature of volcanic units with uniform properties of eolian deposits.

From analysis of the Magellan radiometry results together with SAR images it was found [17] that locally older volcanic units tend to have relatively lower dielectric permittivity of surface material. This shows that some kind of surface aging occurs. The nature of this process is not known: it can be either progressive local chemical weathering or progressive accumulation of eolian deposits. Patchiness of occurrence of dielectric permittivity contrasts between volcanic units points to the latter option. The patches, where such contrasts are observed, perhaps have less extensive coverage with recent surficial deposits; stratigraphically younger units in such regions are places where original volcanic rocks can be easily accessible. Additional studies involving all available remote sensing data are necessary to find good candidate areas and quantify the depth at which bedrocks can be reliably accessible.

**Fresh volcanic rocks:** The observations mentioned above suggest that volcanic units with the highest dielectric permittivity (the lowest microwave emissivity) are places with the least contamination with eolian material, places where original volcanic material can be readily accessible at the surface. The highest dielectric permittivity of lava flows at low elevation (the peculiar material at high latitudes is not considered here) is about 10 - 12. This has been thought to be too high for unaltered volcanic rocks and the transient presence of pyrite has been involved for explanation [18]. This, however, is not necessary, because at Venusian high temperatures the dielectric permittivity of materials is higher than at laboratory temperatures. On Venus, bedrocks of mafic Fe-rich composition can have dielectric permittivity as high as 10 - 12.

### Conclusions:

(1) Mixed dust of ambiguous source and alteration history can contaminate the surface (everywhere) and shallow subsurface (almost everywhere).

(2) If we avoid parabolas, dune fields, etc. and want to get an unaltered sample from a given volcanic unit seen in Magellan SAR mosaics, then a few meters drilling capability is needed.

(3) It is probable that there are regions, where unaltered volcanic bedrock can be reached at the depth of a few decimeters or less. Additional analysis of the available data sets is needed to make an inventory of such regions and reliably estimate the depth.

(4) There are a few small (tens of km) areas, where there is a good chance to access unaltered lavas just at the surface (< 1 cm deep).

(5) Crater-related parabolas give easy access to material ejected by from known site.

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### **Trace gas constituents of the Venus mesosphere measured by SPICAV/SOIR on board Venus Express**

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The SOIR instrument performs solar occultation measurements in the IR region (2.2 - 4.3  $\mu\text{m}$ ) at a resolution of  $0.12\text{ cm}^{-1}$ , the highest on board Venus Express. It combines an echelle spectrometer and an AOTF (Acousto-Optical Tunable Filter) for the order selection.

The wavelength range probed by SOIR allows a detailed chemical inventory of the Venus atmosphere above the cloud layer (65 to 150 km) with an emphasis on vertical distribution of the gases. In particular, measurements of HDO, H<sub>2</sub>O, HCl, HF, CO and CO<sub>2</sub> vertical profiles have been routinely performed. Their isotopologues are also studied, as well as upper limit detection of several other gases, such as SO<sub>2</sub>, H<sub>2</sub>CO, H<sub>2</sub>S and OCS.

Results for selected orbits will be investigated and discussed.

## **VENERA and VEGA Missions to Venus: Historical Highlights**

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### **Abstract**

Multiyear program of Venus exploration in the former Soviet Union is briefly discussed including missions scientific objectives, scenario and the main milestones. Landers robust design and in particular, their capacity to survive in hostile environment on the Venus surface, are specifically addressed. An overview of the scientific results obtained from VENERA and VEGA missions during operation in the atmosphere and on the surface, as well as from the computer modeling, are focused on those relevant to geochemistry of Venus.



**Interactions of Mechanical Controls on Magma Emplacement with the Petrology of Volcanic Edifice-building Flows on Venus.** P. J. McGovern<sup>1</sup> and J. Filiberto<sup>1</sup>, <sup>1</sup>Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston TX 77058, USA ([mcgovern@lpi.usra.edu](mailto:mcgovern@lpi.usra.edu)).

**Introduction:** Large volcanic edifices on Venus constitute a primary expression of the thermal evolution of that planet. Over 150 volcanic edifices with diameters  $> 100$  km are distributed heterogeneously over the surface of Venus [1-4]. They are characterized by extensive radially oriented lava flow aprons and generally shallow flank slopes. The compositions of the lava flows that build such structures potentially record variations in the physical conditions (depths, temperatures of melting, etc.) that govern magma ascent and eruption. In this abstract, we discuss the petrological implications of a recently discovered link between volcanic edifice shape and magma ascent paths that is modulated by lithospheric flexural stresses [5-6]. This link suggests that under certain circumstances, magma may ascend directly from the mantle melt region to the surface, rather than collecting and differentiating in reservoirs at intermediate depths. Furthermore, considerations of buoyancy [7] and enhanced lithospheric stress [8] at the crust-mantle boundary may lead to enhanced magma storage at that horizon. These mechanically based scenarios predict specific trends in major element ratios that may be detectable by instruments on future missions to Venus.

**Mechanics of Magma Ascent:** The state of stress in the lithosphere can exert a major control on the ascent of magma from mantle melting zones [9]. Two criteria for magma ascent must be satisfied [5-6]: 1) principal stress orientations (least compressive stress horizontal [10]) and 2) gradients of horizontal differential stresses (positive gradients, i.e., horizontal compression decreasing with increasing height [9]). To account for the mitigating effects of buoyancy and overpressurization, small adverse values of horizontal compression and stress gradients are considered to satisfy the ascent criteria.

The “dipole” nature of flexural stress dictates that Criterion 1 will be violated in about half of the lithosphere (in the absence of vertically uniform membrane stress), but for small enough stress magnitudes the mitigating effects will overcome this “half-barrier”. In particular, large values of elastic lithosphere thickness  $T_e$  (order 40-50 km) create low enough stress magnitudes to allow ascent via Criterion 1 (see Fig. 1). However, as  $T_e$  decreases, adverse stress magnitudes and stress gradients tend to shut off magma ascent beneath the centers of large loads; preferred ascent paths migrate toward the outer flanks, favoring formation of more domical-shaped edifices. At the lowest values of

$T_e$  ( $< 15$  km or so), adverse compressive stresses and gradients are very high beneath conical and domical edifices. However, annular edifice shapes produce a pair of narrow zones on the inner and outer slopes that satisfy ascent criteria (Fig. 1) at such low  $T_e$  values. Such a scenario can explain the origin of a number of annular edifices on Venus that have been included in the morphologic/structural category of “corona” [e.g., 2].

The interaction between lithosphere thickness  $T_e$  and crustal thickness  $T_c$  also plays an important role in magma ascent. If  $T_c < T_e$ , then the crust-mantle boundary is within the lithosphere. The density contrast between crustal and mantle materials may produce a “density trap” where magmas may stall [e.g., 7] and accrete basaltic materials at the base of the crust, a phenomenon termed “underplating” [e.g., 8]. However, the contrast in stiffness at the crust-mantle boundary may also contribute to underplating, by producing a local maximum in horizontal compressive flexural stress at the top of the mantle [8]. Under either mechanism, magmas may accumulate at the base of the crust and differentiate there; whatever material is not underplated may subsequently erupt at the surface.

**Petrologic inferences of Magma Storage and Ascent:** The systematics of major element abundances determined from analyses of volcanic samples have been used to infer depths at which magmas have collected and differentiated. For example,  $K_2O$  vs.  $SiO_2$  systematics for several terrestrial hotspot-related volcanism locales indicate trends that may be diagnostic of depth of differentiation (Fig. 2). The “base” of the trends outlined in the figure ( $K_2O < 1\%$  and  $SiO_2$  around 50%) corresponds to tholeiitic magmas that ascend directly from moderate-depth ( $< 1.8$  GPa pressure) mantle melt regions, as at mid-ocean ridges. The Vega 2 and Venera 14 measurements [see 12-13] plot in this area and are thus consistent with directly ascent of these magmas from the mantle. We might expect magmas that take the “direct ascent” paths (e.g., Fig. 1) to exhibit similar chemistry, especially for domical and annular edifices that do not tap central magma chambers but rather follow distal ascent paths.

In Figure 2, the green trend line (data from Alcedo in the Galapagos and Thingmuli in Iceland) indicates differentiation at low pressure ( $< 0.2$  GPa, corresponding to about 7-8 km depth). Evidence from GPS and radar interferometric studies of Galapagos calderas [e.g., 14] suggests that magmas are stored in shallow



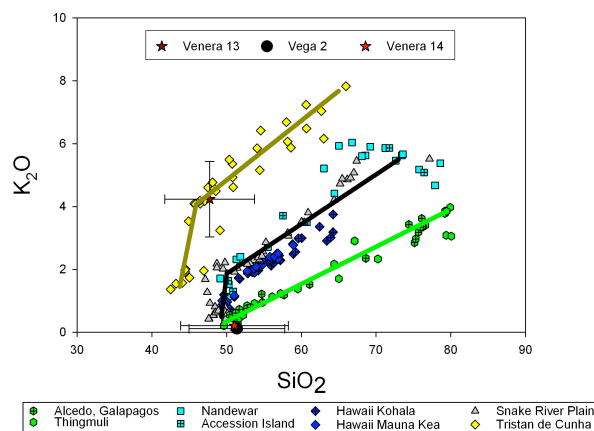
sills, a finding consistent with the expectation of high levels of compressive stresses in the upper halves of thin lithospheres in settings with young oceanic crust (for Galapagos,  $T_c \sim 12$  km [15]).

Magmas that differentiate at somewhat higher pressures (0.5-1.6 GPa, corresponding to perhaps 13-60 km depth, depending on planetary gravity and assumptions about densities and crustal structure) follow the black trend line in Fig. 2. These include Hawaiian lavas that differentiate in the mantle before eruption. We might expect lavas from conical edifices on Venus to resemble products from the more or less conical Hawaiian edifices that are supported by substantial lithospheric thickness ( $T_c \sim 25$ -40 km [see 8]).

Magmas that differentiate at the highest pressures (1.8-2.7 GPa, perhaps 70-120 km depth) produce the trend marked in yellow in Figure 2. The Venera 13 measurement falls within this trend. Such a suite might be seen at volcanoes on Venus where  $T_c$  or  $T_e$  is comparable to these depths (assuming trapping at the crust-mantle boundary or lower lithosphere).

#### Sampling Strategies for Venus:

The best constraints on major element composition (e.g., Fig. 2) for planets like Mars come from rover-based instruments such as the APXS on the Mars Exploration Rovers. Similar point source determinations major element compositions on Venus could determine properties of Venus melts and shed light on the evolution of an individual edifice. To the extent that flows at individual edifices exhibit unique and distinct trends on plots like Fig. 1, a single measurement on a given volcano could in theory provide sufficient information to categorize its differentiation and magma storage history. Thus, an immobile landed probe could provide this information for a specific volcano. However, a more comprehensive test of the proposed link between volcano morphology/shape and magma ascent paths would require measurements from a number of volcanoes. This might be accomplished by a mobile platform, most likely some sort of buoyancy-driven aircraft system (balloon). Such a mission should be targeted for a region which displays a variety of volcano morphologies, such as Eistla Regio [6]. Ideally, remotely sensed spectroscopic data acquired as spatial maps of element concentrations would allow rigorous tests of the ideas presented here. Unfortunately, whatever advantages Venus presents in this regard (absence of dust and erosion compared to, say, Mars) are more than likely wiped out by atmospheric transmission considerations, even for platforms located within the atmosphere on aircraft. Atmospheric alteration of rock surfaces is also a potential pitfall.



**Figure 1**  $K_2O$  vs.  $SiO_2$  showing trends found in terrestrial intraplate suites and their conditions of formation (see [11] in this volume for sources of data). All data renormalized to 100 wt% without sodium or phosphorous to be able to directly compare terrestrial rocks with the Venera and Vega data.

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**SULFUR BEHAVIOR IN TERRESTRIAL BASALTIC MAGMAS: INSIGHTS FOR THE BEHAVIOR OF VOLCANIC SULFUR ON VENUS.** Peter J. Michael<sup>1</sup> <sup>1</sup>Department of Geosciences, The University of Tulsa, 800 S. Tucker Dr., Tulsa, OK 74104, [pjm@utulsa.edu](mailto:pjm@utulsa.edu).

**Introduction:** When considering the possibility of volcanic degassing of sulfur to the atmosphere of Venus, it is instructive to consider the behavior of Sulfur in terrestrial basaltic magmas. Terrestrial submarine basaltic glasses provide a good indication of magmatic sulfur content and behavior because they produce a basaltic glass (a super-cooled liquid) when they erupt on the seafloor.

**H<sub>2</sub>O, CO<sub>2</sub> and Sulfur Degassing:** Sulfur degassing on earth almost never takes place in the absence of significant H<sub>2</sub>O degassing. H<sub>2</sub>O is much more soluble in magmas than CO<sub>2</sub>. Mantle-derived mid-ocean ridge basalts (MORB) contain about 0.1% H<sub>2</sub>O and perhaps 0.1% CO<sub>2</sub>. When they ascend, basaltic magmas become oversaturated with a mixed vapor phase that starts off as nearly pure CO<sub>2</sub> because of the greater solubility of H<sub>2</sub>O. Significant amounts of H<sub>2</sub>O and sulfur are degassed from basaltic magmas only where they ascend to much lower pressures, such as at Iceland and other subaerial volcanoes. The pressure of eruption of submarine MORB is sufficient (100-500 bars) that this point is not reached, so that degassing rarely involves much loss of H<sub>2</sub>O (or sulfur). Plateau basalts such as Ontong Java or Deccan traps have similar H<sub>2</sub>O contents and degassing behavior. In contrast to MORB and plateau basalts, subduction-related magmas have much higher initial H<sub>2</sub>O contents (0.2-5.0 wt.%) and therefore they often lose H<sub>2</sub>O and sulfur by degassing at greater pressures during their ascent through the crust. Ocean island basalts such as Hawaiian basalts have intermediate H<sub>2</sub>O contents and may degas H<sub>2</sub>O and sulfur depending on the initial H<sub>2</sub>O content and the depth of eruption.

On Venus, the atmospheric pressure of 95 bars is sufficient to retain about 1.0% H<sub>2</sub>O in solution. It is unlikely though, that basalts from Venus would contain such high water contents. The present lack of subduction recycling on Venus, and the low H/D ratios in the atmosphere suggest that Venus' interior is rather dry and that magmas are also dry, perhaps similar to MORB. If so, it implies that most basaltic eruptions on Venus will not be accompanied by degassing of water or sulfur. If Venus' mantle has a higher sulfur content than Earth's mantle, it is likely that the additional sulfur would form additional immiscible sulfide blebs in basalt, not a vapor phase.

**Sulfur in solid basalts:** Most basaltic magmas on earth have low oxygen fugacity and contain dissolved sulfide (S<sup>2-</sup>). The sulfide solubility of the silicate liquid is determined largely by its FeO content. Mid-ocean

ridge basalts (MORB) almost always erupt saturated or oversaturated with S<sup>2-</sup>, as shown by the immiscible sulfide liquid blebs their glasses contain and by their linear trend on a plot of FeO *versus* S. Plateau and flood basalts and some MORB that form by very large extents of melting are undersaturated with sulfide. Their silicate glasses have lower S<sup>2-</sup> contents at a given FeO content and contain no sulfide blebs. In either case, the crystallized (non-glassy) basaltic rocks should contain disseminated metallic sulfide minerals that would form whether or not the initial liquids were sulfide saturated. These sulfides are available to equilibrate and react with Venus' atmosphere.

**Thermal structure in the Venusian atmosphere: diurnal and annual variations** A. Migliorini<sup>1</sup>, D. Grassi<sup>2</sup>, G. Piccioni<sup>3</sup>, P. Drossart<sup>4</sup>, A. Cardesin-Moinelo<sup>5</sup>, <sup>1</sup>IASF-INAF (Rome, Italy, via del Fosso del Cavaliere, 100, 00133 Roma, [alessandra.migliorini@iasf-roma.inaf.it](mailto:alessandra.migliorini@iasf-roma.inaf.it)), <sup>2</sup>IFSI-INAF (Rome, Italy, via del Fosso del Cavaliere, 100, 00133 Roma, [davide.grassi@ifsi-roma.inaf.it](mailto:davide.grassi@ifsi-roma.inaf.it)), <sup>3</sup>IASF-INAF (Rome, Italy, via del Fosso del Cavaliere, 100, 00133 Roma, [giuseppe.piccioni@iasf-roma.inaf.it](mailto:giuseppe.piccioni@iasf-roma.inaf.it)), <sup>4</sup>Obs de Paris-Meudon (Meudon, 5, Place J. Janssen, 92195, Meudon - France, [pierre.drossart@obspm.fr](mailto:pierre.drossart@obspm.fr)), <sup>5</sup>ESAC-Madrid ( Villanueva de la Cañada, Madrid, Spain, [alejandro.cardesin@iasf-roma.inaf.it](mailto:alejandro.cardesin@iasf-roma.inaf.it))

**Introduction:** We present a general overview of the Venus mesospheric temperature fields, as retrieved from the data of Virtis-M instrument on board of Venus Express spacecraft, after more than two years of operations [1]. Atmospheric structure is investigated mainly in the Southern hemisphere. Temperature rises poleward along the meridian in a wide range of altitudes. A cold collar centered around 65S is also evident (Fig 1.). Short-time variability of the atmosphere (1h time scale) is dominated by fluctuations peaking at 1 mb, that show maximum amplitudes just after the sunset. Long term variability is also investigated (Fig 2). Temperatures in the lowest part of probed pressure range ( $p < 0.1$  bar) is driven, in the polar region, by the occurrence of polar dipole, whose effects are however limited below 35 mbar.

Mean maps of atmospheric temperature at selected pressure levels are also discussed with respect to local time. In fig. 3, the case of pressure level 90 mbar is shown, obtained by averaging a dataset of 50 frames selected among the whole Venus-Express mission. Atmospheric temperature is in average about 10 K warmer at dusk than at dawn, at 30 to 60 deg South. Close to the pole, the so-called cold collar region is visible, in the latitude range from 60 to 75 deg South. In this region, the variation in temperature with respect to the pole, for instance, is of at least 20 K, as it is clear from fig. 3. The same atmospheric structure disappears moving to higher altitudes (lower pressures maps, not shown here).

The results are compared with the findings from previous missions about the Northern hemisphere [2]. Atmospheric structure follows in average the behavior in the Northern hemisphere.

## Digital Formats:

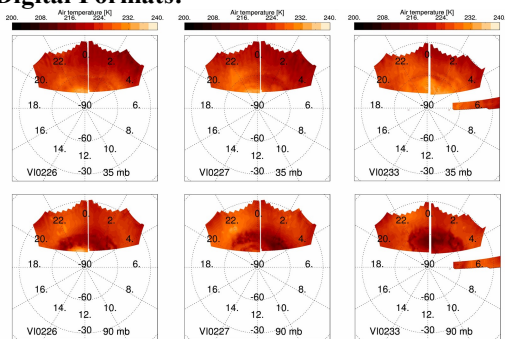


Fig 1. Example of variation from day to day of the atmospheric temperature, for the pressure levels at 35 and 90 mbar.

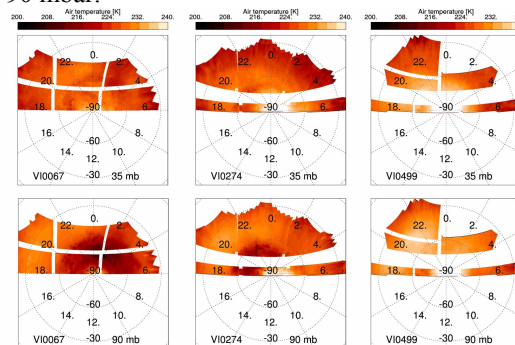


Fig 2. Seasonal variation of the atmospheric temperature in 3 venusian years, for the pressure levels at 35 and 90 mbar.

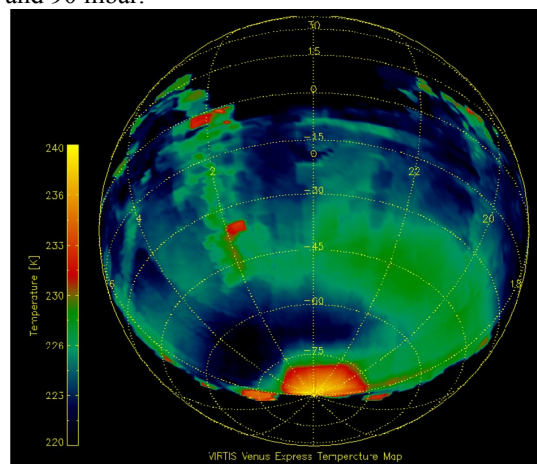


Fig 3. Temperature mean map at a pressure level of 90 mbar. The region around the cold collar is clear at about 60-70 deg in latitude. Temperature is about 10 K warmer at dusk than at dawn side of the planet.

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- [2] Zasova, L. et al. (2007) *PS&S*, 55, p. 1712-1728

**Additional Information:** The research is partly supported by ASI.

## Venus Surface Thermal Emission Observed by VIRTIS on Venus Express

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### Introduction

The imaging spectrometer VIRTIS is the flight spare of the instrument of the same name on the Rosetta mission. It was refitted to be part of the Venus Express mission orbiting Venus since 2006. VIRTIS can observe night-side thermal emissions at the wavelengths of several atmospheric windows. In three of these windows atmospheric transparency is sufficient to allow a measurable amount of radiation originating from the surface thermal emission to escape [1, 2, 3]. Surface emissivity in this near infrared range is indicative of surface mineralogy, observation of the atmospheric windows presents an opportunity to characterize the surface mineralogy globally [4, 5]. In this study, a signal, that can arguably be attributed to surface emissivity, is isolated from VIRTIS images and mosaiced to create a map encompassing most of the southern hemisphere.

### Data Processing

A detailed description of the data processing can be found in [6]. Bands 0 and 30 of VIRTIS -M IR image cubes, accessible at the ESA planetary science archive PSA <http://www.rssd.esa.int/psa>, are corrected for stray-sunlight and limb darkening to retrieve flux of radiation emitted through the windows at  $1.02\ \mu\text{m}$  and  $1.31\ \mu\text{m}$ .

Several factors contribute to the variation of flux at  $1.02\ \mu\text{m}$ . Most important are atmospheric transmittance and surface temperature while emissivity has an unproportionately small influence [7, 5]. Cloud transmittance is determined from  $1.31\ \mu\text{m}$  and applied to  $1.02\ \mu\text{m}$  while accounting for multiple reflections between lower atmosphere and clouds.

The remaining contrast is highly correlated with Magellan altimetry. Owing to the greenhouse climate the surface temperature can be assumed to be constant temporally albeit steadily decreasing with surface elevation [2]. At constant emissivity more radiation is emitted from the hotter lowlands than from highlands. Above lowlands the atmospheric column is higher and extinction of radiation is more severe. Extinction is additionally a function of wavelength. Due to thermal effects the wavelength registration of VIRTIS varies.

The combined effect of surface temperature and extinction is analyzed empirically as the average behavior of 'declouded' flux with respect to topography and wave-

length sampled. Thus characterized average flux establishes a relation between VIRTIS brightness, wavelength and topography. Fig. 1 is a mosaic of all processed VIRTIS images translated to topography and fits well to Magellan GTDR data. Spatial resolution is limited by scattering in the cloud layer to 100 to 120 km, see also [8, 7].

The brightness of VIRTIS images relative to brightness predicted from Magellan topography and wavelength is positively correlated with surface emissivity. To match Magellan and VIRTIS spatial resolutions, all Magellan data points within a radius of appr. 200 km are used to predict NIR flux at the location of VIRTIS pixel using a gaussian weight function of distance with a FWHM of 120 km. The ratio of declouded VIRTIS images and predicted flux is mosaiced and shown in fig. 2. The signal is however very small compared to noise and only areas covered by at least 10 to 20 images are mapped well.

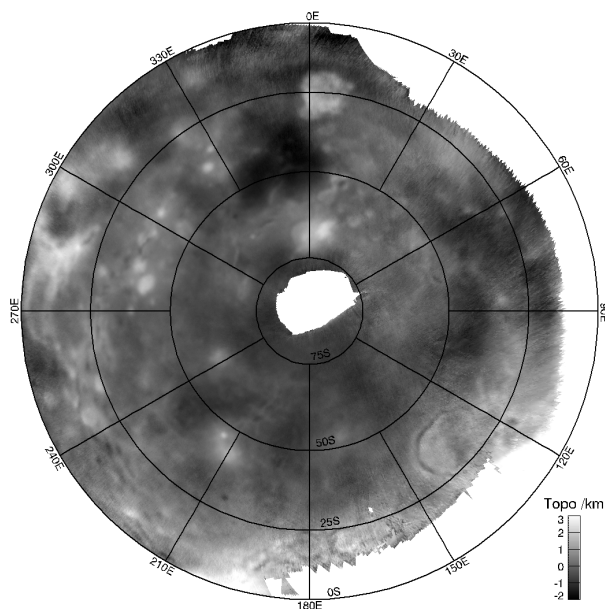


Figure 1: VIRTIS NIR measurements are calibrated with Magellan topography and band wavelength to yield topography.



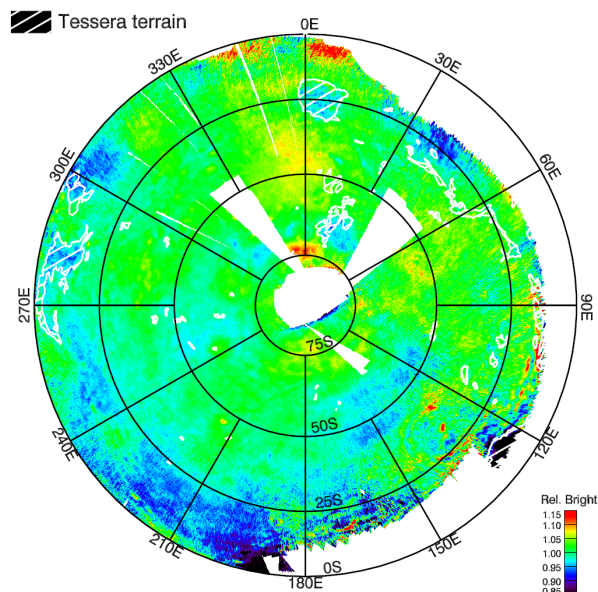


Figure 2: Map of brightness relative to global average indicative of emissivity variation.

## Results

The emissivity variation inferred is to some extent correlated with geomorphological features established from Magellan radar images. Most general result is that tessera highlands have a tendency to emit less than other highland areas of the same altitude. This might indicate felsic surface composition of tessera highlands, e.g. anorthosite or granite [9, 10, 6].

Some, but not all volcanic edifices show increased emissivity. Large lava flows in the Lada terra - Lavinia planitia region also show an increased thermal emission. In particular Cavilaca and Juturna fluctus, emanating from Boala corona (70S 0E) inside Quetzalpetlatl corona, are characterized by an increased IR flux [11].

This might be consistent with large scale extrusive volcanism of ultramafic composition as proposed in [12]. Localized lithosphere delamination in the context of corona evolution might also lead to melts with unusual compositions [13]. Alternatively, the increased emission found at volcanic units, characterized as relatively young, might be due to increased surface temperature, but no compelling evidence for active volcanism was found looking at individual images.

## Discussion

The local deviation of brightness used to infer emissivity can equivalently be interpreted as an error in topography data within an  $\pm 500$  m margin or average surface temperature deviation of  $\pm 4$  K. The Magellan GTDR dataset archived in the PDS shows an obvious artifact in form of an segment with an offset of similar magnitude approximately at -120 deg longitude. In [14] a reprocessed Magellan altimetry is presented which fits better to VIRTIS brightness derived topography and therefore has been used in our data processing. However, especially at tessera terrain there seem to be outlying radar altimeter readings evident in the GTDR dataset as near-equidimensional pits. Filtering for outliers, resulting in exclusion of up to 50 % of GTDR data-points in the calculation of reference NIR flux, did not significantly change our result.

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# VENUS' BULK AND MANTLE COMPOSITIONS: ARE VENUS AND EARTH REALLY TWINS? A. H. Treiman, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058 (treiman@lpi.usra.edu)

**Introduction:** Venus is Earth's twin in size and bulk density [1], but obviously has a very different climate and climate history. Direct comparison of their histories [2] assumes implicitly that they have similar chemical compositions and internal structures; parts of these assumptions are testable with Venera and VEGA chemical analyses of Venus' surface. From available chemical analyses, it is reasonable that the Earth and Venus are indeed twins, with similar bulk compositions (at least for non-atmosphere elements), mantle compositions, and core sizes [3,4]. Such similarity between Earth and Venus is not necessarily consistent with current models of planetary accretion.

**Principles:** Solar system planetary bodies apparently all accreted with cosmochemically refractory elements (e.g., U, Th, Ca, Ti, Al, Mg) in nearly the

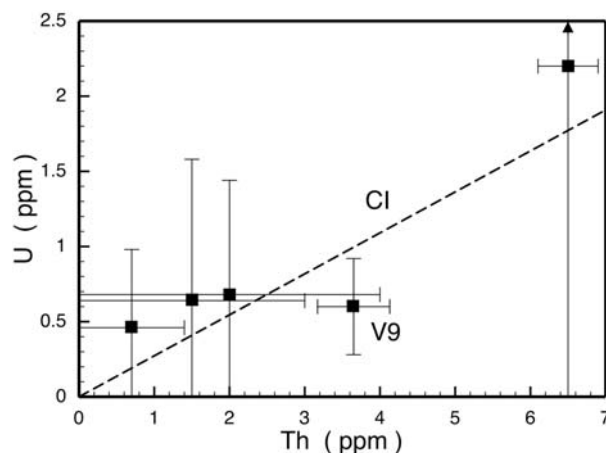


Figure 1 U-Th abundances in Venera & VEGA analyses [5], 'error' bars are  $2\sigma$ . Only the Venera 9 analysis has non-CI U/Th.

same proportions as CI chondrites and the sun [1]. The planets contain less of cosmochemically moderately volatile elements (e.g., alkalis, Fe, Mn, S, etc) than do CIs [1], with depletions in these elements varying among the planetary bodies. After accretion, a planet would differentiate to form a metallic core; Fe and other siderophile elements are partitioned there, while lithophile elements remain in the silicate mantle and crust [6,7]. Finally, the basalts we analyze are generated by silicate melting and crystallization [6,7]; incompatible elements (e.g., U, Th, K, REE) are partitioned into the basalt relative to the abundant solids (from a chondritic base composition), and compatible elements (e.g., Ni) are partitioned into the solids.

By comparing abundances of elements of differing volatility but similar behavior in igneous and core-

forming processes (e.g., K/Th), one learns about the whole planet's volatile content. By comparing abundances of elements that behave differently in core formation, but have similar volatility and igneous behavior (e.g., Fe/Mn), one learns about core formation.

**Data:** Chemical data on Venus' rocks are from the Venera and VEGA landers, summarized by [3,10] with reference to original English publications. Major elements were analyzed by XRF on rock powders, but lack data for Na & Cr. K, Th, and U were analyzed by gamma-ray spectrometry. Here, I assume that the analyzed compositions represent local rocks, unaffected by alteration or weathering (although such effects are possible and possibly significant [8,9])

**Refractories:** Abundances of Th and of U (though relatively imprecise) are broadly consistent with a CI chondritic ratio (Fig. 1). The most precise analysis, V9, has U/Th significantly below the CI ratio. If real, this U/Th could represent fractionation involving garnet, aqueous fluid, or carbonate-sulfate magma [10-14].

Calcium, Ti, and Al are refractory and lithophile in planetary accretion and core formation, and are incompatible in basalt genesis with moderate degrees of partial melting (leaving residue of olivine  $\pm$  orthopyroxene). In a graph of Ca/Al vs. Ti/Al (Fig. 2), basalt melted from a chondritic mantle with ol+opx residua should have chondritic Ca/Al/Ti, and plot near the 1:1 point. Basalts like the eucrites, Earth MORB, and Adirondak-class basalt in Gusev crater (Mars) plot at the CI ratios; Martian meteorite and lunar basalts have superchondritic Ca/Al and Ti/Al, which represent source mantle depletion in Al in early magma oceans.

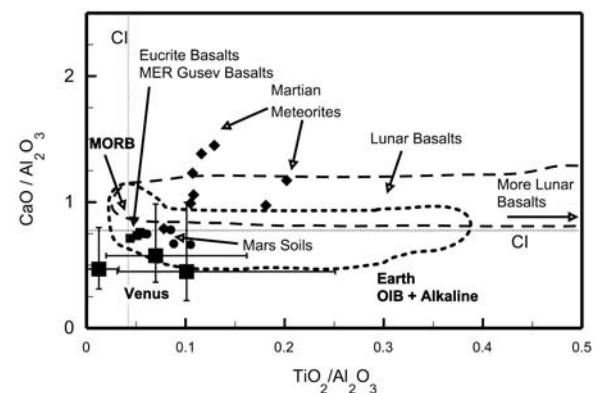


Figure 2. Abundances of Ca, Al, and Ti from Venera & VEGA analyses [5]. MORB, eucrites, and Mars Gusev basalts plot near the CI point, suggesting a relatively undifferentiated source mantle. Martian meteorite and lunar basalts are highly non-CI, consistent with significant differentiation (magma ocean). Venus basalts have ratios near CI; 'error' bars are  $2\sigma$ .

All the Venus basalts could (within  $2\sigma$  uncertainties) have chondritic Ca/Al, but more likely have subchondritic Ca/Al (Figure 2). A possible explanation is that partial melts of dry eclogite (garnet pyroxenite) with MORB-like compositions also have subchondritic Ca/Al [15,16]. On the other hand, Ca could have been lost in weathering [8,9].

**Volatile elements:** Potassium, Fe, and Mn are the moderately volatile elements analyzed by Venera and VEGA. Potassium is lithophile and strongly incompatible, so the K/Th and K/U ratios of Venus' basalts should reflect those of the whole planet. Though imprecise, all but one of the analyses are consistent with those of the Earth: K/U and K/Th  $\sim 0.15 \times \text{CI}$  (Fig. 3). The exception is V9, which also has an anomalous U/Th (Fig. 1). So, the very limited data are consistent with Venus and Earth having similar abundances of volatile elements.

**Mantle & Core:** Abundances of Fe, Mn, and Mg in the Venera and VEGA basalts are comparable to those in Earth basalts, and suggest similar mantle compositions and core sizes.

The FeO/MnO ratio of basalts constrains core formation in a differentiated planet, because Fe and Mn have similar volatility (Mn slightly more volatile) and similar igneous behavior. However, Mn does not enter Fe-rich metal during core formation, so that FeO/MnO tracks Fe-metal separation in a planet. Venera and VEGA data for Mn are imprecise [3,5,10], nearly all as upper limits at the  $2\sigma$  level. If one takes the nominal Mn values as precise, Venus' FeO/MnO is  $\sim 50$ , similar to that of Earth basalts at  $\sim 60$  [10]. Thus, it is reasonable to infer that Venus and Earth have cores of comparable sizes.

Primitive basalts have approximately the same FeO content as the mantle they melted from [17,18]. Magmatic fractionation raises the FeO contents of basalt, so the FeO contents of Venus basalts are upper limits to those of their peridotitic mantle sources. The Venera/VEGA analyses average  $\sim 8\%$  FeO, comparable to those of primitive Earth MORBs. This similarity suggests that the Venus mantle has a FeO content comparable to that of the Earth's mantle.

In a basalt, the ratio  $\text{Mg}^* = 100 \cdot \text{Mg}/(\text{Mg} + \text{Fe})$  [molar] marks both degree of a the basalt's fractionation and partition of Fe between mantle and core. The Venera and VEGA analyses for Mg are imprecise [3,5,10], nearly all as detections at the  $2\sigma$  level. The most precise data are for V2, which yields  $\text{Mg}^* = 73^{+13}_{-21}$ . This value is within uncertainty of those of primitive Earth basalts ( $\text{Mg}^* = 68$ ), which represent equilibrium with mantle olivine of Fo91; again, the Venus mantle composition seems similar to that of the Earth.

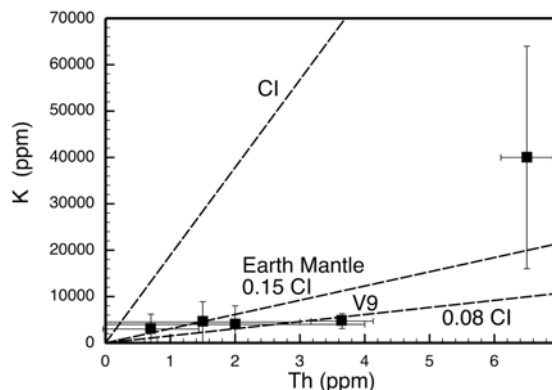


Figure 3. K/Th abundances in Venera & VEGA analyses [5], 'error' bars are  $2\sigma$ . The Venera 9 analysis has non-CI U/Th.

**Conclusion:** Within the imprecise constraints of Venera and VEGA analyses, the chemical compositions of Venus and the Earth are quite similar. Both planets have comparable abundances of a moderately volatile element, K, which suggests that they have comparable abundances of Fe and Mn (somewhat less volatile than K [1]). If so, FeO/MnO and  $\text{Mg}^*$  of the Venus basalts suggest that the Venus mantle has a bulk composition comparable to that of the Earth, and thus that Venus' core is comparable to the Earth's in composition and size. So, the differences between Earth's and Venus' evolutions cannot be ascribed to bulk solid composition, core size, or mantle composition. Also, it is not obvious from dynamical models that Venus and the Earth should have identical or similar compositions [19]. Precise, accurate chemical analyses of Venus basalts will be needed to test these tentative inferences.

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**BASALT-ATMOSPHERE INTERACTION ON VENUS: PRELIMINARY RESULTS ON WEATHERING OF MINERALS AND BULK ROCK.** A. H. Treiman and S. P. Schwenzer, Lunar & Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058. <treiman@lpi.usra.edu, schwenzer@lpi.usra.edu>.

**Introduction:** Chemical interactions between Venus' atmosphere and surface rocks may be crucial to understanding the atmosphere's composition [1-3], and to interpreting surface geology and physical properties [2,4,5]. Most studies have emphasized the atmosphere – its composition and 'chemical sediments,' and few have focused on what happens to basalts and their minerals in reaction with the atmosphere. Our preliminary re-investigation of the mineralogy of altered basaltic minerals and rocks shows that: the anorthite component of plagioclase reacts to anhydrite + andalusite + quartz; diopside pyroxene reacts to anhydrite + orthopyroxene + quartz; and bulk basalt reacts to anhydrite + cordierite + orthopyroxene + quartz ( $\pm$  iron oxide, depending on  $f(\text{O}_2)$ ).

**Venus:** Venus' surface is at  $\sim 740\text{K}$  and  $\sim 96$  bars pressure [5] – a metamorphic environment of 'amphibolite grade,' 'hornfels facies [6];' the paucity of  $\text{H}_2\text{O}$  in Venus' atmosphere ( $30 \pm 15$  ppm) prevents formation of amphibole. Venus' atmosphere, at its surface, is mostly  $\text{CO}_2$  (96.5 %), with significant proportions of S gases ( $\text{SO}_2$ ,  $150 \pm 30$  ppm,  $\text{COS}$   $4.4 \pm 1$  ppm,  $\text{H}_2\text{S}$   $3 \pm 2$  ppm and S, 20 ppb [5,7]). The oxidation state at the Venus surface is not entirely clear, but it probably is relatively oxidizing, above the magnetite-hematite oxygen buffer,  $\log f(\text{O}_2) \sim -21.3$  [8].

Venus' surface materials are known only through the Soviet Venera and VEGA landers, which all landed on lava flows and volcanic constructs [9]. All analyzed materials were of basaltic composition. Here, we work from the V14 basalt, which (within its large imprecision) is similar to Earthly MORB (Table 1), and investigate how a MORB model of the V14 basalt would react at the Venus surface.

Table 1. Basalt Compositions, with uncertainties.

	MORB [10]	1 $\sigma$	V14	1 $\sigma$
$\text{SiO}_2$	49.8	0.37	48.7	3.6
$\text{TiO}_2$	1.45	0.11	1.25	0.4
$\text{Al}_2\text{O}_3$	15.1	0.42	17.9	5.2
$\text{FeO}$	10.3	0.27	8.8	1.8
$\text{MnO}$	0.2	0.03	0.16	0.08
$\text{MgO}$	7.79	0.12	8.1	3.3
$\text{CaO}$	12.4	0.18	10.3	1.2
$\text{Na}_2\text{O}$	2.47	0.12	n.d.	-
$\text{K}_2\text{O}$	<u>0.09</u>	0.03	<u>0.2</u>	0.07
Sum	99.60		95.4*	

\*Does not include  $0.35 \pm 0.3\%$   $\text{SO}_3$ .

**Mineral Reactions:** Reactions between individual minerals and Venus atmosphere were investigated via the SUPCRT code (and self-consistent database)[11], which accesses a large database of minerals, but is designed for aqueous solution chemistry. So far, computations have been done up to 623K with manual extrapolation to higher T with data from [12]. Neither database has values for relevant sulfates besides anhydrite, nor for carbonate or sulfate liquids [13].

The anorthite component of plagioclase can react with the Venus atmosphere:  $\text{CaAl}_2\text{Si}_2\text{O}_8 + \text{SO}_3 \Rightarrow \text{CaSO}_4 + \text{Al}_2\text{SiO}_5 + \text{SiO}_2$  (anhydrite + andalusite + quartz; corundum + quartz is always unstable [14]). This reaction should proceed [2,6], although its equilibrium  $\text{SO}_3$  is close to that of the Venus atmosphere [7,15]; our calculations imply that plagioclase with anorthite activity of  $\sim 0.3$  should be in equilibrium with anhydrite, andalusite, quartz, and the atmosphere. The albite component of the plagioclase remains in feldspar (jadeite is unstable at Venus surface P [6]).

Among mafic minerals, diopside is calculated to react via  $\text{CaMgSi}_2\text{O}_6 + \text{SO}_3 \Rightarrow \text{CaSO}_4 + \text{MgSiO}_3 + \text{SiO}_2$ . This reaction should proceed to near completion in the Venus atmosphere [7,15,16], leaving pyroxene with diopside activity  $\sim 0.05$ . Enstatite and forsterite remain stable, while ferrosilite and fayalite may oxidize/sulfidize to iron oxides/sulfides and quartz.

**Bulk Rock Reaction:** Our second approach is to model the reaction of a bulk basalt (Table 1) with the Venus atmosphere. This model would correspond to alteration of basalt glass, or of a crystalline basalt with easy element diffusion between crystals. We determine the equilibrium mineralogy of that basalt at Venus surface p-T-X, using analog systems, chemography, and thermochemical calculations [17]. Analog and synthetic systems and their chemography are summarized in [6], but few such systems take into account the high  $f(\text{SO}_2)$  of the Venus surface. Thermochemical calculations are done (so far as possible) with Thermocalc® and its self-consistent database [18,19], which does not include S-bearing species. To apply that code and database, we assume that all CaO in the model basalt reacts with atmospheric  $\text{SO}_2/\text{SO}_3$  to form anhydrite,  $\text{CaSO}_4$ . This assumption is justified by the mineral reaction results above, and results cited in [2,7,16,17]. We further assume that: {1} carbonates are not stable [16]; {2} no other sulfate phases form; {3} volatile-bearing silicates (scapolites, micas, amphiboles) do not



form; and {4} Na and K reside in alkali feldspar (not in sulfates, carbonate melt, or feldspathoids). The last assumption is reasonable here (Table 1), but will not be appropriate for K-rich basalts (Venera 8,13). We consider two simple cases: reduced, in which Fe is treated as a divalent cation and lumped with Mg and Mn; and oxidized or sulfided, in which Fe is assumed to all be reacted to form an oxide (hematite or magnetite; [8,20] or a sulfide (pyrite; [21,22]).

Table 2. Masses of Alteration Products from 100 grams of MOR Basalt (Table 1), & Volume Change on Alteration.

Grams	Case 1 – Divalent Fe	Case 2 – All Fe as hematite
Anhydrite	28.3	28.3
Albite	21.4	21.4
Cordierite	30.8*	30.1
Enstatite	26.4*	8.9
Quartz	5.1	13.67
Hematite	0	11.5
Total Mass	112.0	113.9
Δ Volume %	+12	+14.6

Assumes all anorthite component reacts to form anhydrite.

\*With Fe/Mg ratio of bulk rock.

Volumes calculated for 25°C, 1 bar.

In the first case (Fe as a divalent cation), removal of Ca as anhydrite and Na & K as 'albite' yields a residue with molar ratios Si:Al:'M' of 2.1:1:1.6 ('M' = molar Mg+Fe+Mn). This material is inferred to equilibrate to anhydrous cordierite + enstatite + quartz [23], Table 2 (pyrope & sapphirine are unstable at Venus surface P [24,25]; spinel + quartz is unstable at Venus surface T [26]). In the latter case, in which Fe is allowed to be oxidized to hematite by the atmosphere, the alteration assemblage remains the same but the proportions of enstatite and quartz change (Table 2).

**Implications:** Within the available datasets and current understanding of Venus' atmosphere and rocks, it appears that the principal reaction at the Venus surface will be production of anhydrite from essentially all the Ca in basaltic minerals and rocks. Iron in the rocks and minerals will likely react to either oxides or sulfides, depending on the oxidation state of the atmosphere. The fate of alkalis is not clear – our calculations yield only alkali feldspar (albite), but alkalis could be partitioned into ionic (carbonate-sulfate) melts [13]. Some Venus basalts are so rich in potassium that phases besides feldspar may be present (e.g., leucite, nepheline-group, or sodalite-group).

In Venus surface weathering, sequestration of Ca in anhydrite and Fe in iron oxide (sulfide) leaves the residue rich in Al and Si, which then equilibrates to anhydrous cordierite + enstatite + quartz (Table 2). Weathering causes a significant increase in mass and volume

(Table 2), most of which derives from formation of anhydrite. However, a portion of the increase comes from formation of quartz and cordierite, which both have open crystalline structures. The volume increase could be responsible for the platy structure visible in lander images of the Venus surface.

**Prospects:** This work is preliminary, with several areas of improvement forthcoming. First, the thermochemical databases lack several phases and components needed for full treatment: S-bearing gas and mineral species into the Thermocalc<sup>®</sup> database; Fe- and Mg-sulfates need to be added, as do those on S-bearing silicates (e.g., sulfate scapolite, S-sodalite); and explicit consideration of ionic melts. Solid solutions need to be considered explicitly. We look forward to Venus Express' new constraints on the composition of Venus' atmosphere.

**Acknowledgments.** Both authors are grateful to the LPI for support of this work, and to NASA HQ for supporting the Venus Geochemistry workshop.

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**PLANETARY RAMAN SPECTROSCOPIC STUDY FOR UNDERSTANDING VENUS EVOLUTION HISTORY.** Alian Wang, Dept. Earth and Planetary Sciences and McDonnell Center for Space Sciences, Washington University, St. Louis, MO, 63130 (alianw@levee.wustl.edu).

**Introduction:** Venus is an extremely interesting place to study the evolution history of a planet. It has a dense and highly corrosive atmosphere, which would react with the minerals at the surface of planet under very high temperature and high pressure conditions. S-cycling is the major and crucial process that needs to be well understood for the purpose of study the evolution history of Venus. Planetary Raman Spectroscopy is well suited for this task.

**Planetary Raman Spectroscopy:** By sending a condensed laser beam onto a target (gas, liquid, or solid) and by collecting the induced back-scattering Raman radiation, one can extract information on the chemical bonding in molecules, crystal structures, and chemical compositions. Planetary Raman spectroscopy is well suited for Venus exploration for the following reasons: (1) It is definitive; i.e., minerals are unambiguously identified through their fingerprint spectra. Raman peaks are sharp and non-overlapping; straightforward identification of phases in a mixture can be achieved from raw spectra. Spectral deconvolution in general is not required. (2) Analyses are rapid, requiring only a few seconds to half a minute to obtain a spectrum. (3) No sample positioning or sample preparation are required: original rough surfaces of rocks and soils give informative Raman spectra; the gaseous components in the atmosphere can be detected by sending the excitation laser beam through a short distance in the air (a few cm on Earth and even shorter distance on Venus). (4) Photons from excitation laser and Raman scatters can penetrate through optically transparent material (i.e. window) that would facilitate a variety of instrument deployments during a mission.

**Investigation of S-cycle on Venus:** S-bearing species,  $\text{H}_2\text{S}$  &  $\text{SO}_2$  as gases,  $\text{SO}_3$ ,  $(\text{SO}_4)^{2-}$ , and  $(\text{HSO}_4)^-$  in aqueous solutions,  $\text{S}_8$ ,  $\text{Fe}_2\text{S}$ , sulfides, and sulfates as minerals, are all very strong Raman scatters. Because the Raman cross sections of many gaseous species are known, the partial pressure of a gaseous S-species in a mixture (Venus atmosphere) can be calculated from the relative intensity of its characteristic Raman peak. The concentration of  $\text{H}_2\text{SO}_4$  in a

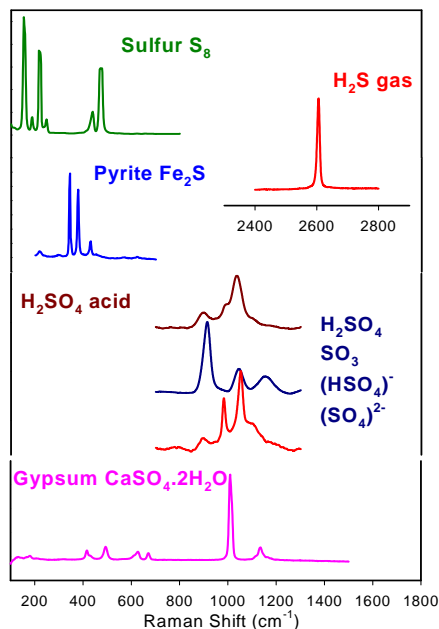
water droplet (aerosol) can vary in a range, which will affect the types and the concentrations of various S-species dissolved in the water, such as  $\text{SO}_3$ ,  $(\text{HSO}_4)^-$ ,  $(\text{SO}_4)^{2-}$ , and  $\text{H}_2\text{SO}_4 \cdot n\text{H}_2\text{O}$  complexes. They all have distinct Raman peaks that would enable their direct identifications (Figure).

We have been conducting a systematic Raman (combined with XRD, mid-IR, and Vis-NIR) investigation [1, 2] on Mg-, Ca-, and Fe-sulfates (hydrous and anhydrous, crystalline and amorphous), to set constraints on the phase stability and phase transition pathway under variable environmental conditions, such as temperature, pressure, relative humidity, acidity, and oxygen fugacity. In addition, a Raman study on Fe-oxides, hydroxides, and sulfides was published [3]. These investigations have built a knowledge basis for developing an understanding about the surface-atmosphere interaction on Venus.

The applications of Planetary Raman Spectroscopy for igneous mineralogy and petrology on planetary bodies (Moon and Mars, as well as for Venus) are characterized by providing “definitive mineralogy,” that includes mineral identification, determination of key mineral chemical compositions, the relative proportions of different minerals in a rock or soil as well as textural relationships of mineral assemblages [4, 5, 6]. This type of investigation will shine light on the planet’s early igneous chemical differentiation, as well as the later stages of weathering caused by recent volcanic activities.

**Acknowledgement:** NASA PIDDP and MIDP program supports for developing the Mars Microbeam Raman Spectrometer, NASA MFRP program for Martian sulfates study, and McDonnell Center for Space Science at Washington University for laboratory supports.

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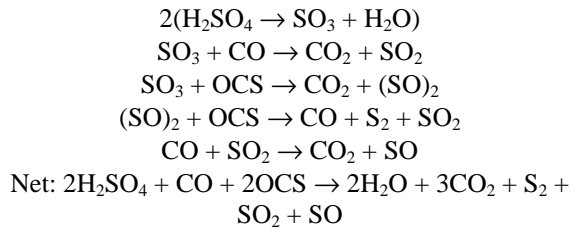
Atmospheric Constraints on Sulfur Reactions Fluxes at the Surface of Venus

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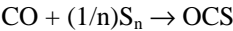
**Introduction:** It was only a few decades ago when we discovered that the clouds of Venus are made of sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), and only in recent years did we know that carbonyl sulfide (OCS) is the major carrier of sulfur from the surface to the middle atmosphere. Due to the lack of an ocean, most of sulfur species on Venus reside in the atmosphere, attaining concentrations 10<sup>5</sup> times those in the terrestrial atmosphere. Sulfur chemistry is critical to the composition of the Venus atmosphere [1], and four sulfur species have been firmly identified: SO<sub>2</sub>, SO, OCS, and H<sub>2</sub>SO<sub>4</sub> (vapor and in aerosols). Strong absorption in spectrophotometer data from VENERA 11 and 12 at 450-600 nm between 10 and 30 km has been attributed variously to gaseous elemental sulfur, polysulfur (S<sub>x</sub>), or SO<sub>2</sub>. The presence of thiozone (S<sub>3</sub>) and polysulfur in the clouds has been inferred.

**Two Types of Chemistry:** The chemical regimes in the atmosphere of Venus vary from photochemistry in the middle atmosphere to thermal equilibrium chemistry in the lower atmosphere and the surface [2]. Recent data of OCS and CO from ground-based and Venus Express observations provide a unique opportunity for advancing our understanding of chemistry and transport in the lower atmosphere of Venus. The combination of data and modeling provides strong evidence for the loss of OCS by conversion to CO in the lower atmosphere. The total loss rate of OCS in the lower atmosphere is about 23,000 Tg-S/yr [3]. This is a robust result that does not depend on the details of the model. The surface of Venus must supply OCS at this rate to maintain the concentration of OCS in steady state in the atmosphere. The implications for surface chemistry are discussed.

**Equilibrium Chemistry:** While the chemistry of sulfur in the atmosphere above the clouds is fairly well understood, this is not true in the lower atmosphere and at the surface, where reactions such as the following have been proposed but are poorly understood [4]:

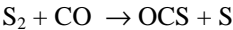


and

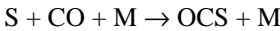


What are the most stable forms of S in the lower atmosphere? The possible forms of S include S<sub>n</sub>, where n = 1 to 8. In thermodynamic equilibrium at the surface of Venus, the relative partitioning of S<sub>n</sub> is summarized in Table 1. S<sub>2</sub> is the most abundance sulfur species.

The following reaction has also been suggested [4]:



It is known that



Together, these two reactions may restore the OCS that is lost in the middle atmosphere.

Table 1. Relative concentrations of S<sub>n</sub> species in mole fractions. The numbers a(-b) read as ax10<sup>-b</sup>.

Species	Abundance
S	5.07 (-17)
S <sub>2</sub>	1.66 (-7)
S <sub>3</sub>	5.59 (-10)
S <sub>4</sub>	2.81 (-12)
S <sub>5</sub>	1.04 (-12)
S <sub>6</sub>	4.76 (-14)
S <sub>7</sub>	4.03 (-16)
S <sub>8</sub>	1.06 (-17)

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**ON THE COMPOSITION OF PUTATIVE OCEANS ON EARLY VENUS.** M. Yu. Zolotov<sup>1</sup> and M. V. Mironenko<sup>2</sup>, <sup>1</sup>School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, e-mail: zolotov@asu.edu. <sup>2</sup>Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, 19 Kosygin Str., Moscow 119991, e-mail: mironenko@geokhi.ru.

**Introduction:** Venus once had substantially more water and possibly even oceans early in its history. Given the close proximity of Venus and Earth, the planets could have accreted comparable amounts of volatiles. The high D/H ratio in the atmosphere of Venus implies an elevated water abundance earlier in the history of Venus [1,2]. This water was lost by mechanisms that may have involved evaporation under runaway greenhouse conditions, photo-dissociation of H<sub>2</sub>O, and water-rock reactions [1]. Preferential hydrodynamic escape of hydrogen released through H<sub>2</sub>O dissociation [3] could have caused net oxidation of rocks and atmospheric gases, and accumulation of deuterium in the atmosphere [1-3].

The existence of early oceans should have affected the subsequent evolution of the atmosphere and lithosphere. The involvement of aqueously altered and oxidized rocks, and oceanic sediments (e.g., salts) in lithospheric processes could have influenced rock deformations, melting and degassing patterns, the composition of igneous rocks, and distribution of volatiles in the lithosphere-atmosphere system. In addition to the D/H ratio, signatures of ancient aqueous processes could be manifested in the chemical and isotopic composition of the current atmosphere and lithosphere, in geological features, and in lithospheric geophysical data. These signatures could vary depending on formation scenarios, composition, and loss mechanisms of the early hydrosphere. Here we discuss and roughly evaluate chemical scenarios of early aqueous evolution.

**Evolution of Venus' hydrosphere:** Outer solar system planetesimals containing water ice and/or hydrated minerals could have delivered Venus' water. The same planetesimals probably supplied Cl (as HCl clathrates and/or secondary phases). These and local planetesimals delivered C, N, and S (in organic matter, troilite, and secondary carbonates, sulfides, and sulfates). Impacts during late stages of accretion led to degassing of H<sub>2</sub>O, HCl, and some other volatiles. The low luminosity of the young sun and limited amounts of atmospheric greenhouse gases may have allowed condensation of water. Dissolution of HCl and CO<sub>2</sub> in the aqueous phase led to acidic solutions that reacted with rocks. These reactions caused some neutralization of solutions and precipitation of secondary phases. The primordial surface waters could have been mostly metal (Na, Ca, K, Mg) chloride solutions.

Intensifying high-temperature (*T*) processes in the interior led to differentiation and development of igneous

activity in the upper mantle. High *T* also favored dehydration of the interior and oxidation of C and N in organic compounds. Some H<sub>2</sub>O was consumed through oxidation of Fe<sup>0</sup>-metal, and S, C, and N species leading to the production of H<sub>2</sub>. Early magmatic gases delivered H<sub>2</sub>, CO, H<sub>2</sub>O, CO<sub>2</sub>, H<sub>2</sub>S, S<sub>2</sub>, HCl, and N<sub>2</sub> into the atmosphere and hydrosphere.

Below are several possible scenarios of oceanic evolution. I) The formation of abundant H<sub>2</sub> through oxidation by H<sub>2</sub>O of the interior led to the production of CH<sub>4</sub>, which accumulated in the atmosphere. Corresponding strong greenhouse heating caused evaporation of fluids and precipitation of chlorides. Hydrogen was then lost through hydrodynamic escape [3] and CH<sub>4</sub> was oxidized to CO<sub>2</sub>. II) An intense supply of acidic species (HCl, H<sub>2</sub>S, CO<sub>2</sub>, CO) toward the surface and a limited exposure of silicate rocks led to low-pH oceans and the accumulation of CO<sub>2</sub> in the atmosphere, which increased greenhouse heating and atmospheric pressure (*P*). This pathway may have caused rapid evaporation of fluids and precipitation of chlorides. III) A limited supply of acidic species, large continental areas, and permeable suboceanic rocks would have favored neutralization of solutions and trapping of a substantial CO<sub>2</sub> mass in carbonates. Corresponding water reservoirs survived longer and were oxidized through hydrogen escape. Evaporation of these reservoirs led to salt deposits containing chlorides and carbonates. IV) If not abundant, surface aqueous solutions could have been consumed through hydration and oxidation of rocks followed by dehydration due to the greenhouse effect. Formation of chlorides is also likely in this scenario.

**Modeling approach:** We developed chemical equilibrium models to explore the above scenarios, though calculations of atmospheric *P* and *T* have yet to be coupled with these models. It is assumed that the majority of C, N, and Cl was extracted/degassed into the atmosphere-ocean system on early Venus, and the speciation of all of the elements was controlled by thermochemical equilibria among gases, solids, and aqueous species. These equilibria were calculated in the O-H-C-S-Cl-N-Na-K-Mg-Fe-Ca-Si-Al system with the GEOCHEQ code [4]. Achaean basalt was used to exemplify the rock composition. We explored effects of the water/rock mass ratio (*W/R*), *T*, *P*, and *f*O<sub>2</sub> (with open system calculations) on the composition of aqueous and gas phases, and secondary mineralogy. Basic calculations were performed for *T* = 50°C to 350°C, *P* = 7 bar to 180 bar, and *W/R* = 0.3 (~1 km deep global ocean interacts with ~1 km thick rock layer). Mass balances of CO<sub>2</sub> and N<sub>2</sub> corresponded to today's atmos-

phere of Venus; and Cl (as HCl) and S abundances were represented by the Earth's ocean and crustal reservoirs scaled to Venus' mass [5].

**Results and discussion:** Basic modeling indicates that hot oceanic water could be a  $\text{CaCl}_2$ -NaCl-rich solution with a salinity of ~70-400 g/kg solution. Major aqueous species are  $\text{Cl}^-$ ,  $\text{Na}^+$ ,  $\text{NaCl}^0$ ,  $\text{CaCl}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{CaCl}_2$ . Dissolved  $\text{CO}_2$  and aqueous species of K and Mg are less abundant. Neither sulfide ( $\text{HS}^-$ ,  $\text{H}_2\text{S}^0$ ) nor sulfate ( $\text{SO}_4^{2-}$ ) sulfur is abundant. At higher  $T$ , neutral aqueous complexes become more abundant, and the Ca/Na ratio tends to increase. The pH is typically from 6 to 7. However, the pH is lower if the mass of reacted rocks is smaller (at elevated  $W/R$  ratios) and/or at higher atmospheric  $P$ , which corresponds to elevated  $\text{PCO}_2$ .

The dominance of Cl, Ca, and Na in oceanic water is accounted for by the large mass of Cl and its preferential accumulation in the aqueous phase, and by the limited amounts of secondary minerals of Na and Ca. Calcium is abundant in basalts, and precipitations of anhydrite ( $\text{CaSO}_4$ ), Ca-carbonates, and Ca-phylosilicates still allow accumulation of Ca in solution. Aqueous Mg species are not very abundant because of the formation of dolomite and Mg-phylosilicates. Concentrations of K species are limited by precipitation of K-feldspar, smectites, and K deficiency in rock. Aqueous concentrations of sulfate and sulfides are limited by precipitation of anhydrite and pyrite, respectively. In contrast to low- $T$  oceans of Earth, precipitation of  $\text{CaSO}_4$  prevents the formation of sulfate-rich oceanic water even at very oxidized conditions.

The modeling does not reveal conditions that are favorable for the formation of a Na-carbonate "soda" ocean that would trap the majority of atmospheric  $\text{CO}_2$ . Assumed high abundances of HCl and  $\text{CO}_2$ , and trapping of Na in albite, play roles in preventing the development of a "soda" ocean. Therefore, formation of Na carbonates was unlikely upon evaporation of early oceans.

**Secondary mineralogy.** The models reveal significant hydration of suboceanic rocks and some oxidation of S and Fe in minerals. Major secondary minerals are phyllosilicates (chlorite, montmorillonite, saponite, talc, tremolite, kaolinite), quartz, albite, microcline, carbonates (dolomite, ankerite, calcite), pyrite, and anhydrite. Some assemblages contain hematite (especially at high  $T$ ) or magnetite. At elevated  $f\text{O}_2$  (when much  $\text{H}_2$  escapes), hematite and anhydrite compose the majority of Fe and S minerals, respectively. Higher atmospheric  $P$  leads to lower pH and may prevent formation of carbonates.

At the specified amount of volatilities, the  $W/R$  ratio is the major parameter that affects the redox state, secondary mineralogy, and speciation of coexisting oceanic water and the gas phase. The  $W/R$  ratio may represent thickness of the rock layer involved into the water-rock interaction. At lower  $W/R$  ratios, the mineral assemblage becomes

more reduced. For example, pyrrhotite and magnetite can be present instead of pyrite, anhydrite, and hematite. At high  $W/R$  ratios, acidic and oxidized ( $\text{HCl-CO}_2$ ) solutions coexist with a quartz-rich rock formation. Note that a decrease in  $W/R$  ratio may also represent a vertical profile through suboceanic rocks. The uppermost layer would be rich in quartz, intermediate layers contain the assemblage observed in our nominal models (phylosilicates, quartz, anhydrite, pyrite, carbonates, etc.), and lower layers are only slightly oxidized and hydrated.

**Atmospheric composition.** Our models produce a near-ocean atmosphere that contains mostly  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{N}_2$ . Volume fractions vary as follows,  $\text{CO}_2$ , ~0.3-0.9;  $\text{H}_2\text{O}$ , ~0.01-0.6;  $\text{N}_2$ , ~0.02-0.15. Higher  $T$  leads to higher  $\text{H}_2\text{O}/\text{CO}_2$  and  $\text{H}_2\text{O}/\text{N}_2$  ratios. Higher  $P$  corresponds to lower  $\text{H}_2\text{O}/\text{CO}_2$  and  $\text{N}_2/\text{CO}_2$  ratios. In contrast, the formation of abundant carbonates at lower  $W/R$  ratios increases the  $\text{N}_2/\text{CO}_2$  ratio. Low  $W/R$  ratios also favor formation of methane. However, methane becomes abundant only if a significant amount of  $\text{H}_2$  is supplied from the interior and the synthesis of hydrocarbons is efficient.

**Implications for subsequent history and Venus exploration:** The evaporation of Venus' oceans could have caused local precipitation of chlorides atop hydrated rocks that contained quartz, carbonates, anhydrite, pyrite, and Fe(III) oxides. Subsequent greenhouse and/or endogenic heating(s) may have caused major dehydration and decarbonation, while some subsurface calcite could have equilibrated with Ca-silicates and  $\text{CO}_2$ . Anhydrite, pyrite, and Fe oxides may control abundances of S gases and the atmospheric redox state throughout history [5]. Quartz-rich, partially hydrated, and chloride-bearing rocks could be easily involved in anatexis.  $\text{CaCl}_2$  and NaCl could form a eutectic ( $T = \sim 580^\circ\text{C}$ ) melt, which would affect lithospheric viscosity and convective heat transfer. The formation of Venus' channels [6], crater outflows, and alkali-rich rocks (Venera data) could have been related to this low- $T$  and chemically active melt. If chlorides are present in channels, this would be an indication of aqueous processes on early Venus. Other indications would be an elevated concentration of Cl in alkaline rocks and the presence of schists, quartzites, or banded iron formations.

**Acknowledgements:** This work is supported by NASA PGG research grant.

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